AN INVESTIGATION INTO THE CAUSES OF THE POSITIVE SEA SURFACE TEMPERATURE ANOMALY IN THE NORTHEAST PACIFIC

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THE POSITIVE SEA SURFACE TEMPERATURE

ANOMALY IN THE NORTHEAST PACIFIC

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by

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ABSTRACT

Factors affecting the heat content of the ocean's surface layer are briefly discussed. Some recent studies of sea surface temperature (SST) anomalies are reviewed. The SST anomaly in the NE Pacific, June-October 1967, is described. The influence of individual parameters (1000mb wind, advection, mixed layer depth, net heat exchange, convergence-divergence) on the development and dissipation of the SST anomaly under investigation is evaluated. The simultaneous interactions of the parameters during the period of the study are discussed. Movement of the SST anomaly is described. Warmer than usual advection of surface water and high values of net heat exchange were necessary but not sufficient conditions for development of the SST anomaly. The critical importance of horizontal convergence in the surface layer and relatively shallow mixed layer depth is determined.

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1. Introduction

In 1967 a strong and large positive sea surface temperature (SST) anomaly persisted from June into November in the northeast Pacific Ocean. The relatively large surface area covered by the anomaly and its unusually high magnitude offered an excellent opportunity for study of atmospheric and oceanic parameters contributing to this unusual heating of the surface waters.

The effect of heat exchange, advection and mixing on changes in the heat content of the surface layer has become relatively well known in recent years. Yet the interaction of these and other parameters which cause anomalous SST changes and how their relative contributions to the net temperature change vary with time is not well understood. SST anomalies cannot be attributed to one or two parameters alone and their effect on the heat content of the surface layer. Rather there is an interaction of several parameters at times complementary in nature and at other times in opposition. In this study a single well-developed SST anomaly has been chosen and an attempt is made to correlate its development and decline with atmospheric and oceanic parameters. These qualitative interrelationships between the parameters and the anomaly will then show the complex nature of the formation of a sizable region of anomalous SST's and perhaps will indicate certain requirements that will have forecasting application.

Computer products of the Fleet Numerical Weather Facility have made available more simultaneous meteorological and oceanographic

information covering larger areas than ever before. This information has made it possible to study the development of a SST anomaly simultaneously with the sequential changes in the parameters affecting its development. In this study, 30-day means of SST anomaly were first compared synoptically with the 30-day means of selected parameters in order to establish qualitative relations between the individual parameter and the anomaly. Where mean values were not available, inferences were made from available data, e.g., advection due to surface drift currents was deduced from 1000mb wind charts. Then the anomaly and the parameters were studied simultaneously in order to show the sequence of events during the period of the study. In this way one can see how the individual parameters affected the growth of the anomaly and also that in order for the anomaly to grow and persist as it did, there was required a warming action of all the parameters, not just one or two, in the region of development.

2. Background

The major causes of changes in SST are net heat exchange, mixing, and advection. These factors are not all simple in nature, but are complex and variable forces acting simultaneously on the surface layer of water. Although knowledge of these causes of heat change is constantly expanding, exact descriptions of the heat-exchange processes still are not available.

Net heat exchange, Q_n, across the air-sea interface is comprised of several processes as shown by the formula

$$Q_n = Q_s - Q_r - Q_b - Q_e - Q_h \quad , \qquad (1)$$

where Q_s = insolation

Q_r = reflected radiation

Q_b = effective back radiation (long wave)

Q_e = heat loss due to evaporation

Q_h = heat conduction across the interface .

Laevastu (1960) and Tabata (1962) have developed empirical relationships for calculating the components of Q_n and methods of forecasting the general thermal structure of the ocean. As discussed by James (1966), both studies have found general acceptance. Two sets of formulas in operational use today are presented in the appendix.

Changes in the thermal structure due to heat exchange across the interface depend on several variables: optical properties of the water, radiation wave length, and salinity of the water all affect the rate of absorption of solar energy; while thickness of the mixed layer determines

the temperature increase or decrease per unit of Q_n. Winds determine the rate and depth of mixing, and rate of heat gain or loss determines the rate of change in the thermal structure.

It is seen that changes in the thermal structure depend on several processes, not entirely independent of each other. The variable rates at which these processes occur determines the ultimate change in the thermal structure.

Advection in this report is defined as the horizontal transport of water due to the surface (1000mb) wind field. The rate of advection is, then, a function of the wind speed. As shown by Laevastu (1960), the temperature change at a point per unit time can be easily computed by the formula:

$$\frac{dT}{dt} = kW \frac{dTw}{dx} \tag{2}$$

where $\frac{dT}{dt}$ is local change of temperature per unit time due to advection, W is wind speed and $\frac{dTw}{dx}$ is change of water temperature with distance in the direction from which advection occurs, and k is a constant.

In this study, 30-day mean charts are used for large scale (time and space) studies. Therefore, the absolute rate of advection is not as important as the direction relative to normal from which surface water is being advected.

In his comparative study of direction of surface drift currents with respect to 1000mb winds, James (1966) finds generally that surface drift currents occur 20 degrees to the right of the surface winds. Then, since

surface winds generally act 20 degrees to the left of the geostrophic wind, one can assume drift currents flow parallel to the 1000mb contours.

Mixing can be divided into two categories, depending on whether the cause is (1) wind or turbulence, or (2) convection. Convective mixing is more dominant in winter, while wind mixing dominates in summer.

Wind mixing is defined as "the vertical mixing of water as a result of motions generated by the wind" [James (1966)] . The name "wind mixing" is a misnomer. Actually the wind is the indirect cause. The direct cause is wave action. The thermal structure of the surface layer can change rapidly due to wave action. James (1966) cites the study where gale winds (37 knots) for one day increased the depth of the mixed layer from about 20 meters to 60 meters.

Mixing action also depends on drift currents which are a function of wind force, duration and fetch. In addition, convergence or divergence and the original thermal structure will influence the depth to which wind mixing occurs.

Convective mixing is due to instability of the water column. If the surface layer becomes denser due to cooling or increased salinity (from evaporation), the heavier water will sink causing an overturning or mixing of the layer. As this study pertains mainly to a warm anomaly, convective mixing will not be considered.

Until recently, a systematic study of SST anomalies has been hampered by a lack of accurate SST analyses on a synoptic basis (accuracy of SST data is discussed in Section 3). Therefore, studies of SST

anomalies, and their causes and effects, generally have been unexplored. Study of previously-mentioned parameters causing anomalous SST's is well advanced, but knowledge of exactly how these parameters "work together" to form large areas of anomalous temperature is lacking.

In a brief study of SST anomalies in the western North Atlantic, Lee, Cockrum and Laevastu (1967) studied anomalies for the months of February to July over a period of four years. They found a definite relationship between the combined advective and thermal effects due to atmospheric pressure distribution (winds) and the occurrence of SST anomalies.

The relationship between anomalous solar radiation, Q_S, and SST anomalies was investigated by Hanzawa (1962). Since Q_S is the main source of energy for heating surface water, variation in Q_S reaching the sea surface must cause variation in the amount of heat supplied to the water. He found unusually high values of Q_S associated with SST anomalies and concludes that an excess or deficit in solar radiation will bring about in situ warming or cooling of the surface water. His conclusions were borne out by statistical calculations.

In a study of causes of short-period changes of SST and SST anomalies, Hubert and Laevastu (1966) found evidence that, in most cases, changes in the properties of surface layers were due to atmospheric processes. The surface pressure pattern and its influence on wind-drift currents is extremely important. The authors demonstrated the effects of heat exchange, advection and convergence-divergence on

short-period temperature changes in the surface layers, pointing out that changes in the surface layers (SST, mixed layer depth, etc.) can occur as rapidly as changes in surface weather. Normally these forcing functions are variable in their effect on the surface layers causing little more than transient changes. Occasionally warming or cooling influences will dominate in a general area causing large-scale and persistent anomalies in sea surface temperatures.

In an attempt to develop a tool for use in long-range weather forecasting, Namias (1959, 1963) has investigated relations between SST anomalies and some atmospheric and oceanic parameters. He explained causes of warm SST anomalies as: (1) horizontal convergence in the surface layer causing an absence of upwelling, (2) air-sea temperature difference less than normal accompanied by lighter than normal winds causing less turbulent heat exchange, and (3) advection of water from a more southerly (warmer) source than normal. Namias also suggested that increased insolation aids development of anomalous SST's, but because of lack of data , he did not investigate this aspect.

Lee, Cockrum and Laevastu (1967) in their study of SST anomalies in the western North Atlantic Ocean found the anomalies to persist, usually for several months. Winter anomalies, formed in late fall and early winter, tend to persist into spring. Corresponding surface pressure patterns were also persistent during the period of the anomaly's existence. Because of increased stability caused by warmer than usual surface layers, positive anomalies tend to be more persistent than

negative anomalies. Cooling effects needed to diminish a positive anomaly are of larger magnitude than are warming effects needed to diminish a cold anomaly.

3. Data

The main source of data used in this study was the Fleet Numerical Weather Facility (FNWF). Supplementary data were obtained from the Bureau of Commercial Fisheries (BCF), La Jolla, California, and from the publication Monthly Weather Review (1967). The following data and information were used in the study:

(1) SST anomalies; 5- and 30-day means

(2) SST; 5- and 30-day means

(3) 1000mb isotachs; 5- and 30-day means

(4) 1000mb heights; 5- and 30-day means

(5) Potential Mixed Layer depth; 30-day means

(6) Net heat exchange; 30-day means (FNWF and BCF)

(7) 700mb heights; 30-day means (Monthly Weather Review).

Because of the large scale of the data charts and due to the numerical methods used in their derivation, the accuracy of the analyses cannot be vouched for. SST charts, for example, are based on 3 1/2 days of reports with a weighting procedure emphasizing the more recent data [Hughes (1966)] .

Mean charts prepared by FNWF are derived by calculating the average of all analyses computed for the period of the mean chart. Most analyses are produced twice daily. Thus, 5-day mean charts are the average of 10 analyses and 30-day mean charts are the average of 60 analyses. Concerning terminology, a 5-day mean chart in later sections is designated by its terminal data; the "5 June chart" for example, is the 5-day mean for 1-5 June.

4. The SST Anomaly in the NE Pacific June - October 1967

In late May 1967 an area of surface water which was warmer than usual appeared in the eastern North Pacific Ocean. The SST anomaly grew in magnitude and area through August and then gradually diminished. The anomaly was noted by three separate sources. Fleet Numerical Weather Facility (FNWF) (monthly SST charts), the Bureau of Commercial Fisheries, La Jolla (personal communication), and Wagner (1967), were in good agreement as to position, size and magnitude of the SST anomaly.

Figure 1 shows the growth of the anomaly using 5-day mean anomaly values. The values plotted are the maximum magnitude of the SST anomaly. There is a general, though not continuous, increase in magnitude through late August when the maximum anomaly, +3.9 C, was reached. Thereafter the magnitude decreased, again, though not continuously. After October, the anomaly became indistinct, breaking up into several small areas.

The warm anomaly reached its maximum surface area in July and August. Figures 2a-e show monthly position, magnitude (30-day mean) and movement. In general, the anomaly increased in horizontal area while the anomaly magnitude increased and decreased in area with decreasing magnitude. The region of this study was terminated arbitrarily at 30N and 165W.

The anomaly moved generally to the east from its beginning through August, then turned toward the south. Speeds, determined from center

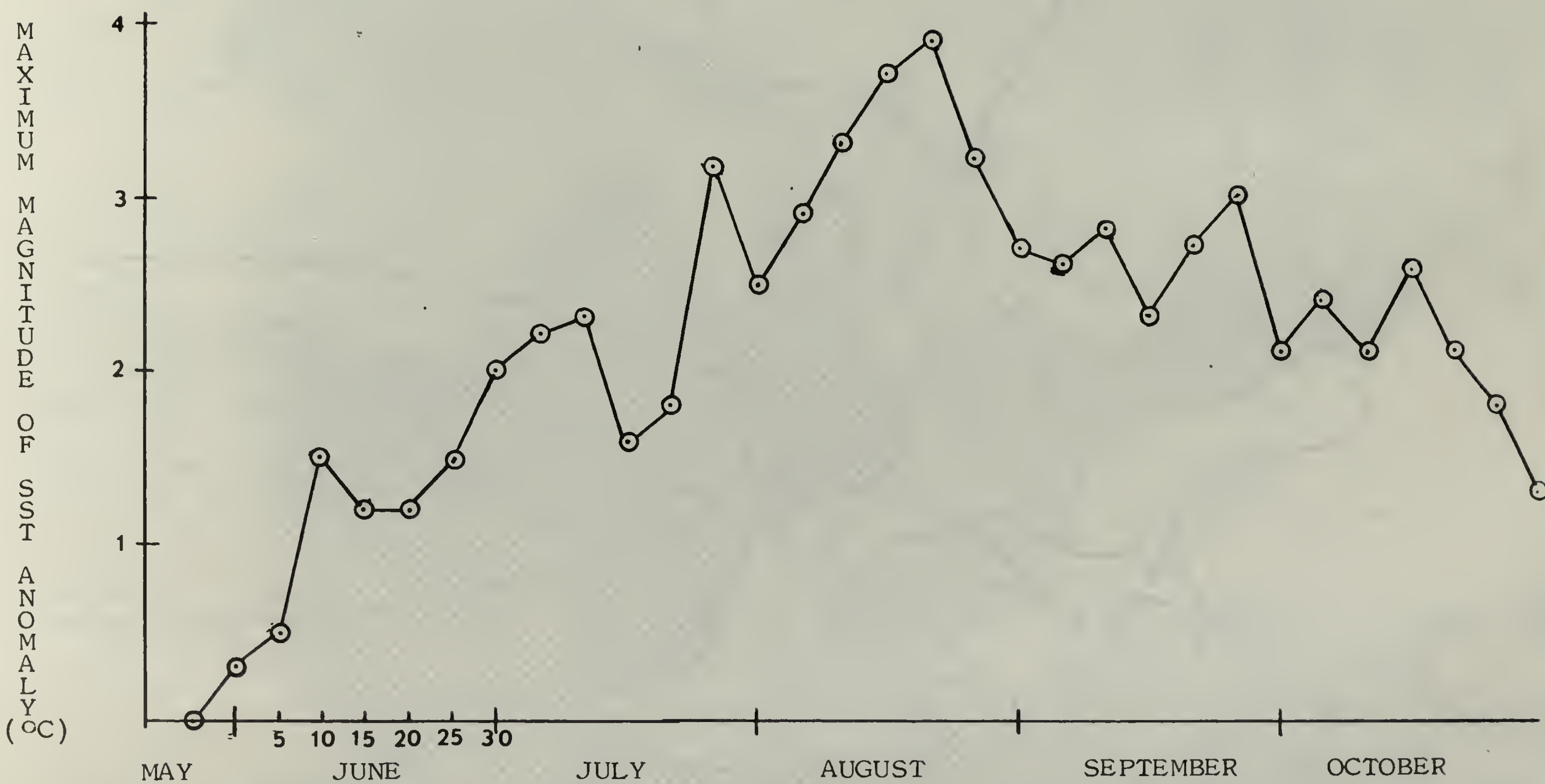

Figure 1. Maximum magnitude of the SST anomaly using 5-day means.

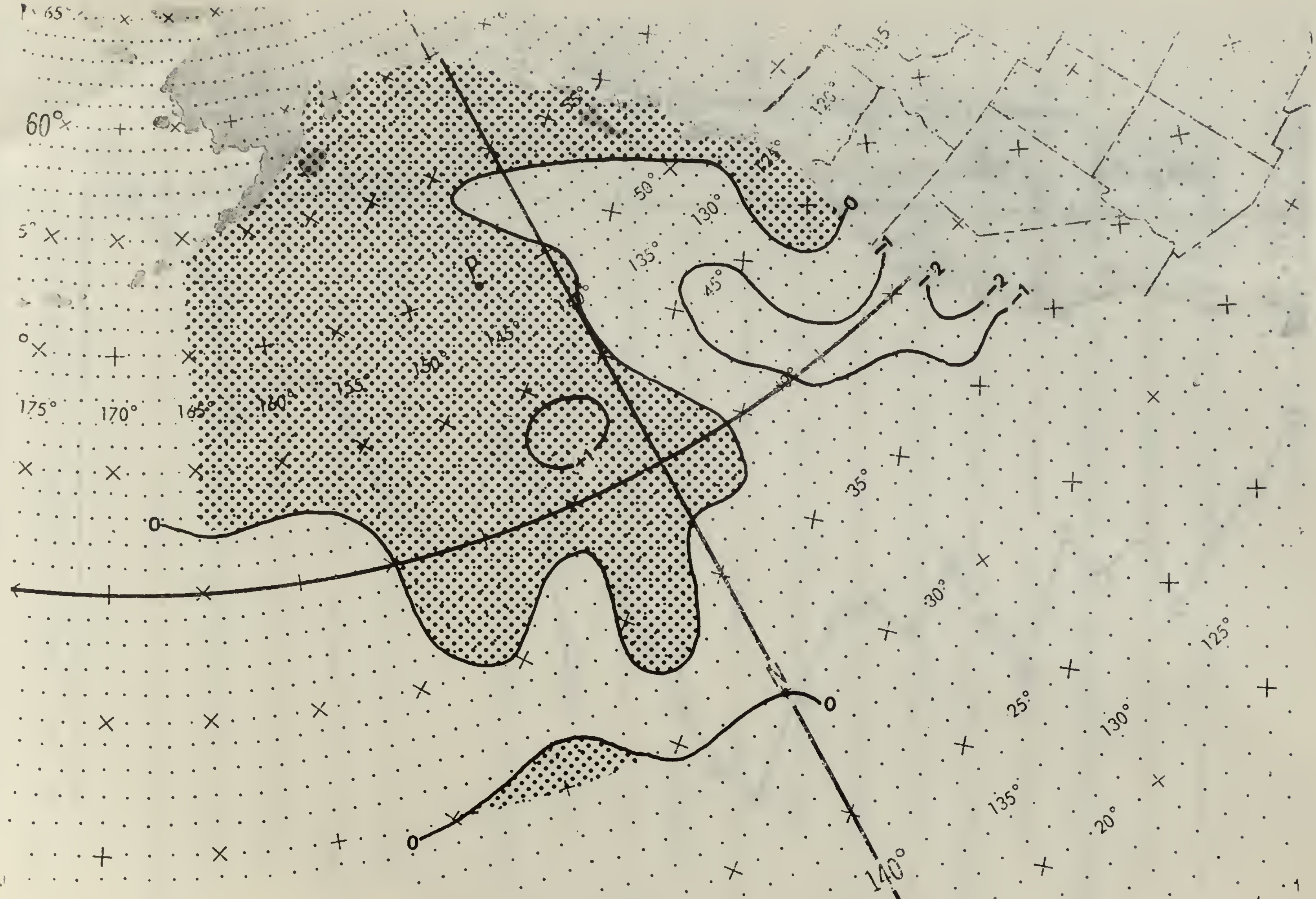

Figure 2a. June mean SST anomaly(°C). Positive(warm) anomaly shaded.

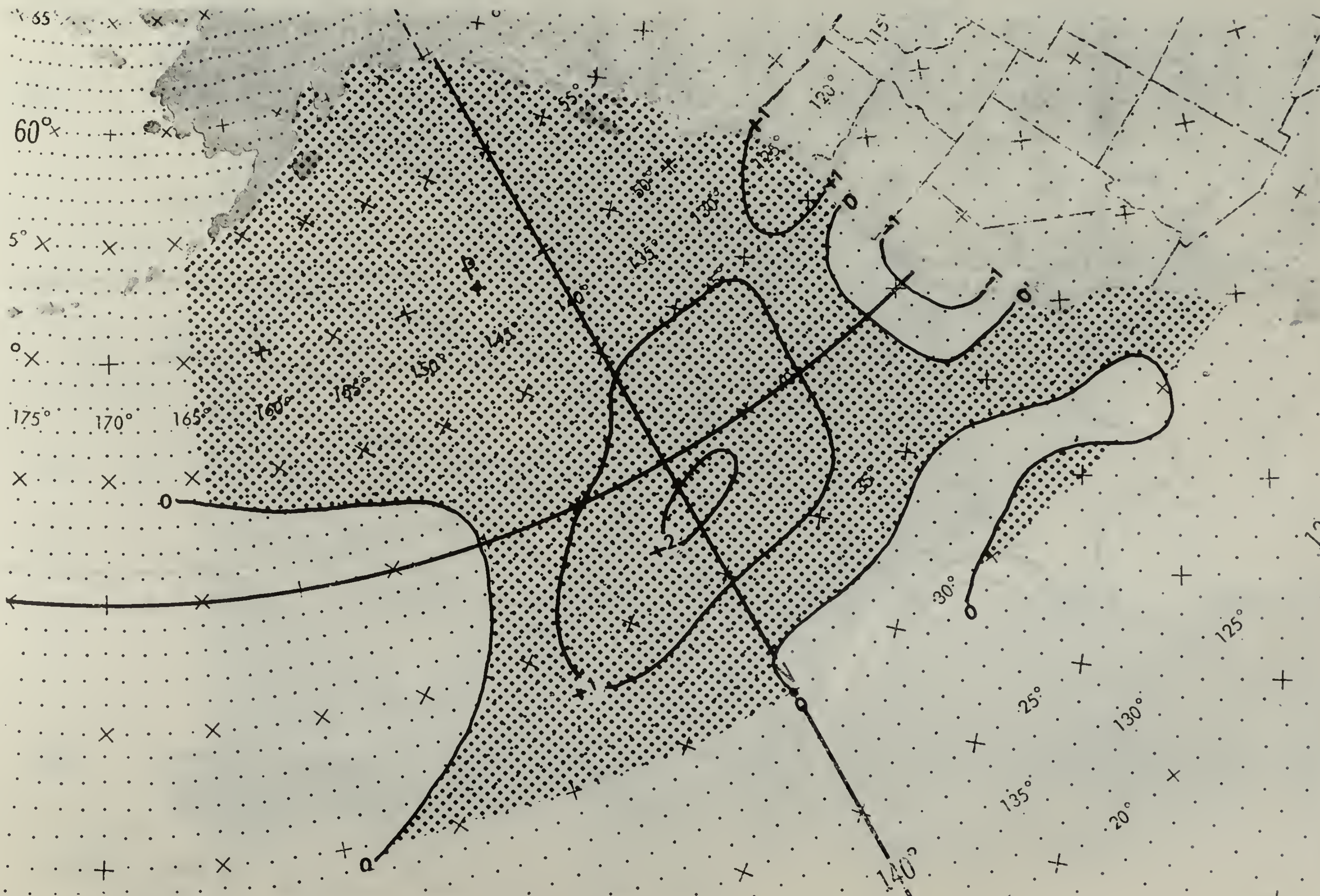

Figure 2b. July mean SST anomaly(^{O}C).

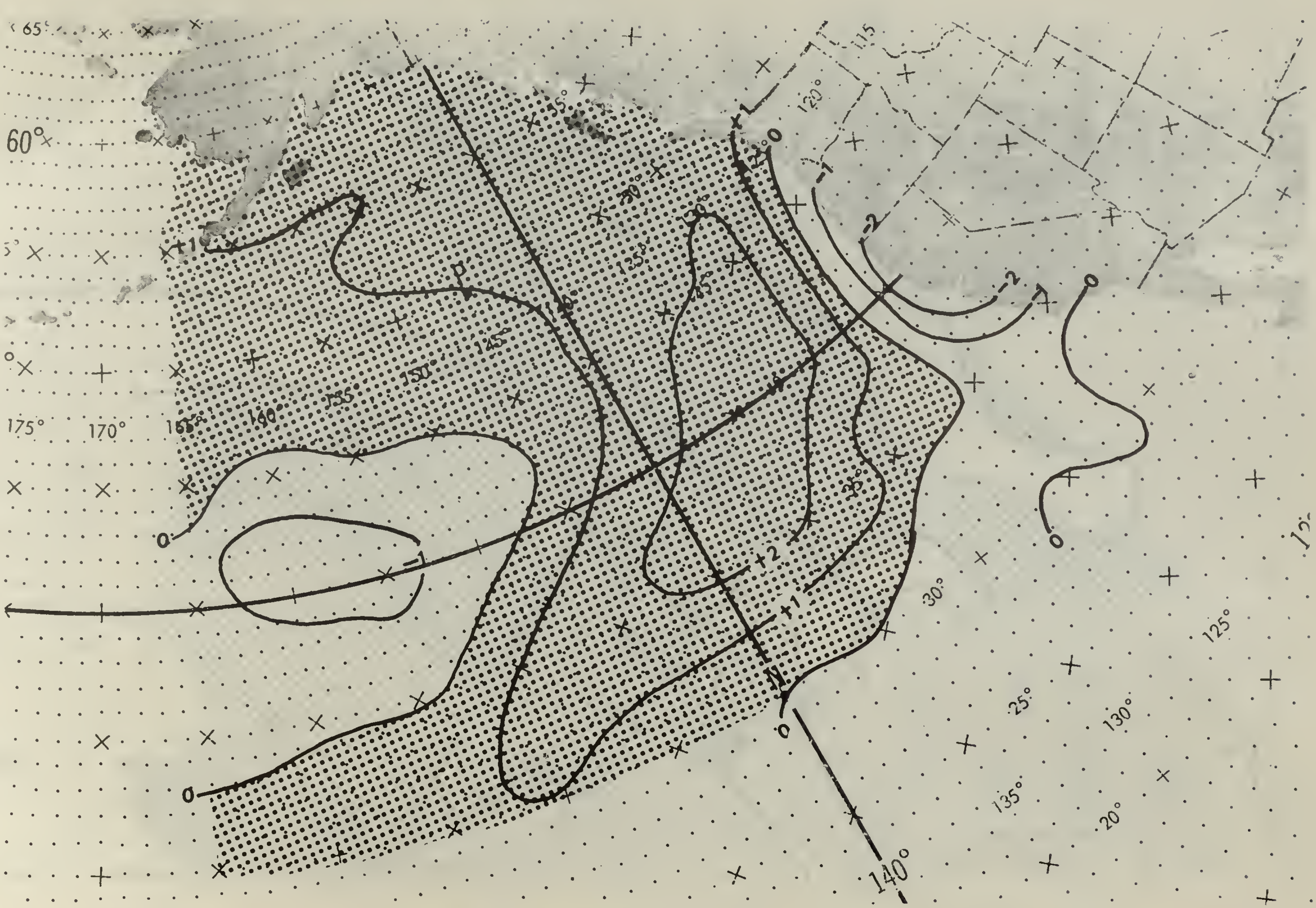

Figure 2c. August mean SST anomaly(^{o}C).

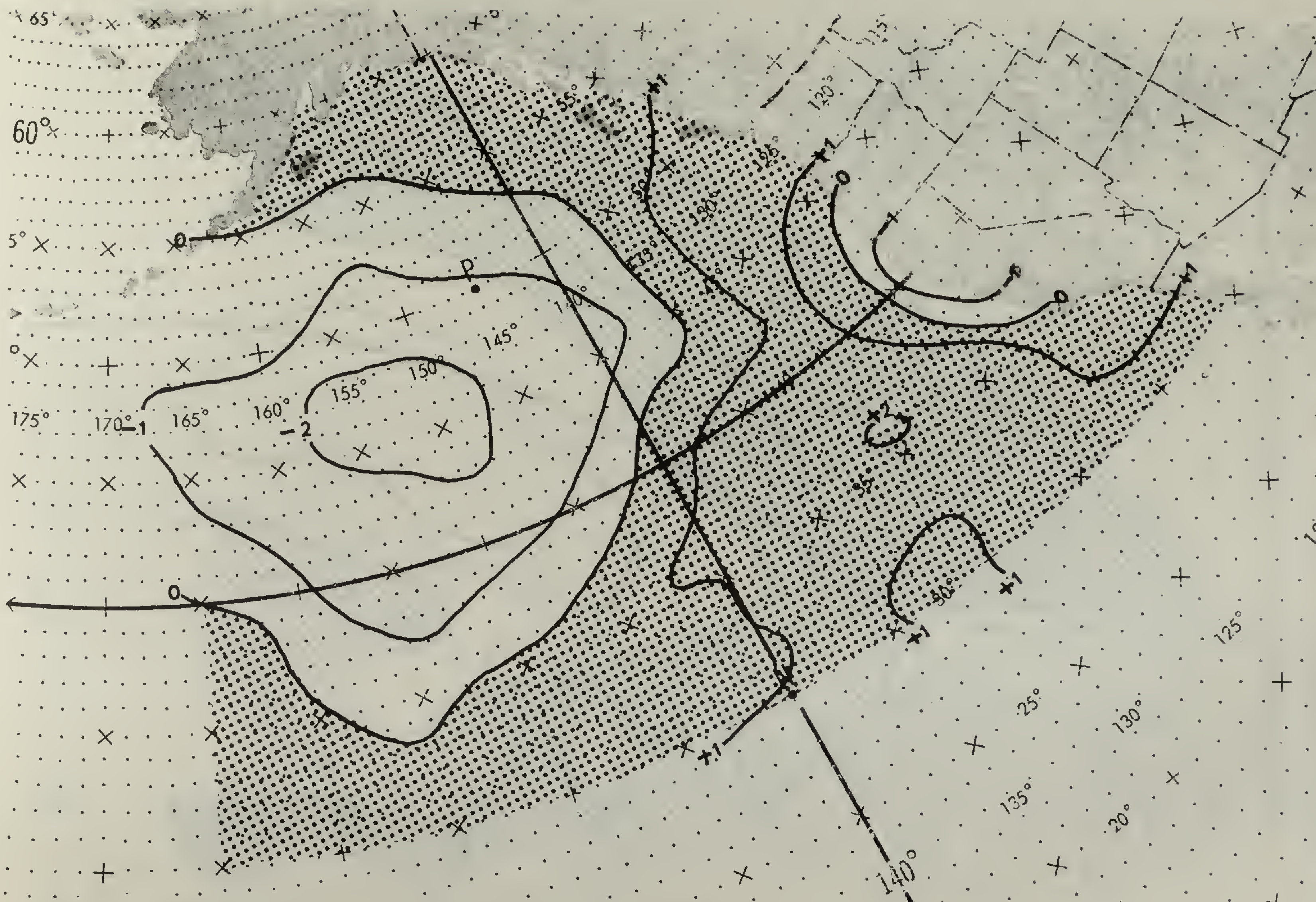

Figure 2d. September mean SST anomaly(^oC).

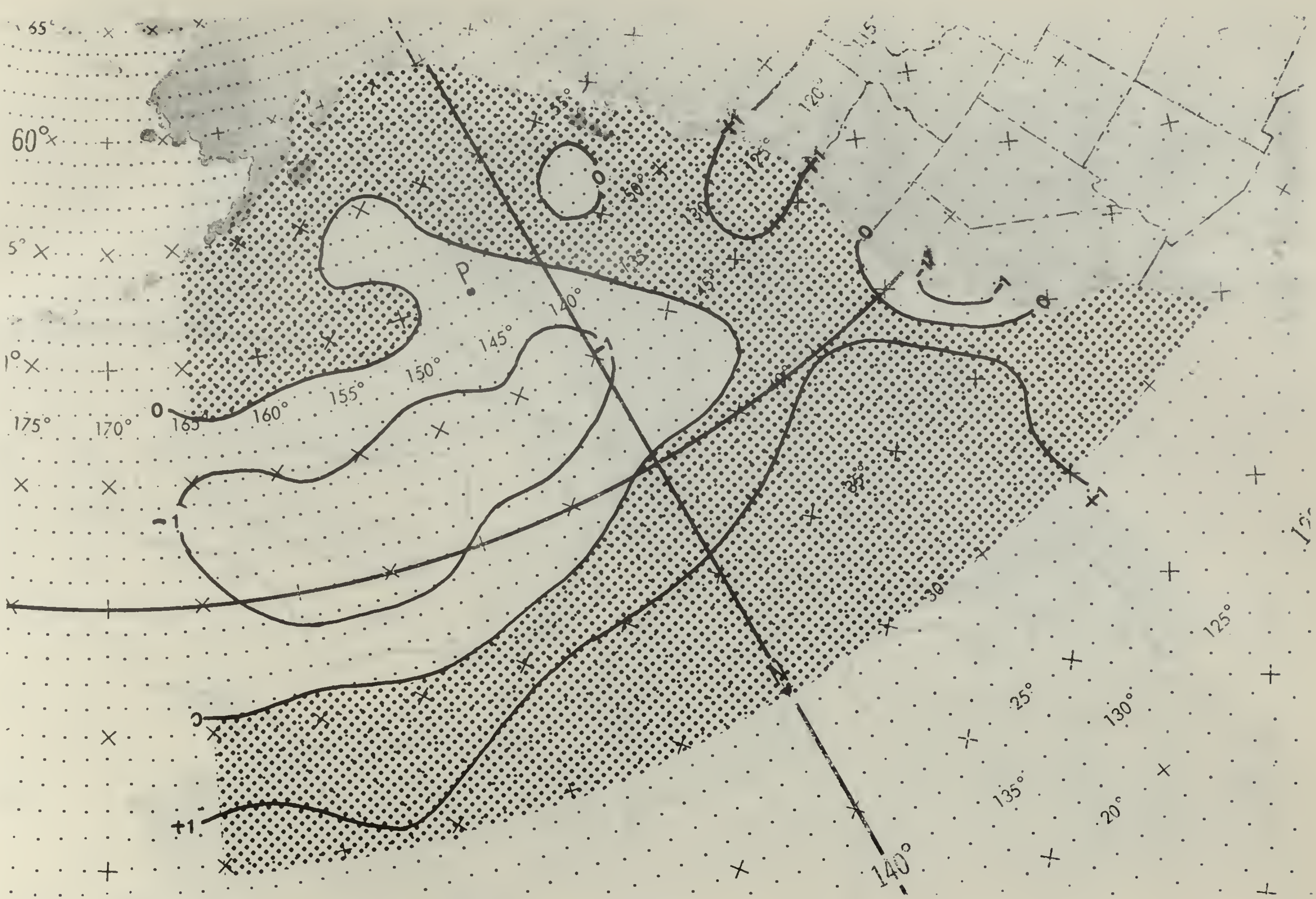

Figure 2e. October mean SST anomaly(^{o}C).

positions, ranged from 0.2 to 0.5 knots. In August, the anomaly diverged to the northeast and the southeast in the area where the North Pacific Current divides into the Alaska and California currents.

5. Influence of Individual Parameters on the SST Anomaly

It has become apparent that SST anomalies are caused by a combination of the effects of several atmospheric and oceanic parameters. Wind speed and direction, advection, net heat exchange at the sea surface, mixed-layer depth, convergence-divergence and probably other factors all affect the SST to varying degrees. In this section the relationships between these parameters and the SST anomaly of 1967 are investigated individually. Section 6 will show the simultaneous effects of the parameters on the development of the anomaly.

5.1 Wind Effects

The effect of surface winds on the thermal structure of the ocean is extremely important. Wind speed and duration determine the rate and depth of wind mixing. Ekman's empirical formula can be used to compute rates of transport of surface water due to wind stress [James (1966)].

$$\frac{v}{w} = \frac{0.0172}{\sqrt{\sin_\theta}} \quad , \tag{3}$$

where w is wind speed, v is current speed, and θ is the latitude. The direction of the surface winds determine the temperature of advected water relative to normal.

In this report 1000mb charts were used instead of surface pressure charts for investigating wind effects. The choice was one of necessity since the 1000mb charts were readily available at FNWF.

Monthly mean 1000mb charts in the area of the anomaly are shown in Figures 3 a-e which display isotachs (of wind) of 15 knots and greater and streamlines. For each month there is a general correlation between areas with winds less than 15 knots and the SST anomaly. The correlation is strongest for the months July-September when the anomaly was strongest. Wind mixing, which is directly proportional to wind speed, presumably was at a minimum in the region of the anomaly. As a result of reduced mixing, the mixed layer depth (MLD) must have been relatively shallow. Thus, other processes causing heating of the surface layer would have a thinner layer of water to affect.

The fact that wind mixing is an important factor in the development of SST anomalies, both positive and negative, is shown in Figures 3 c-e. While light winds are associated with the positive anomaly, the converse is shown as well, since the negative anomaly to the west was clearly associated with stronger winds. In September and October, maximum winds were directly over the maximum negative anomaly.

5.2 Advection

Advection of water due to wind-driven surface currents can cause a substantial effect on the SST. With respect to formation and maintenance of SST anomalies by advection, the direction from which advection occurs is the most important factor. Figures 4 a-c show monthly means of surface pressure for 1967 compared to long-term means. In May (Fig. 4a) the advection (parallel to the isobars) was somewhat more from the south

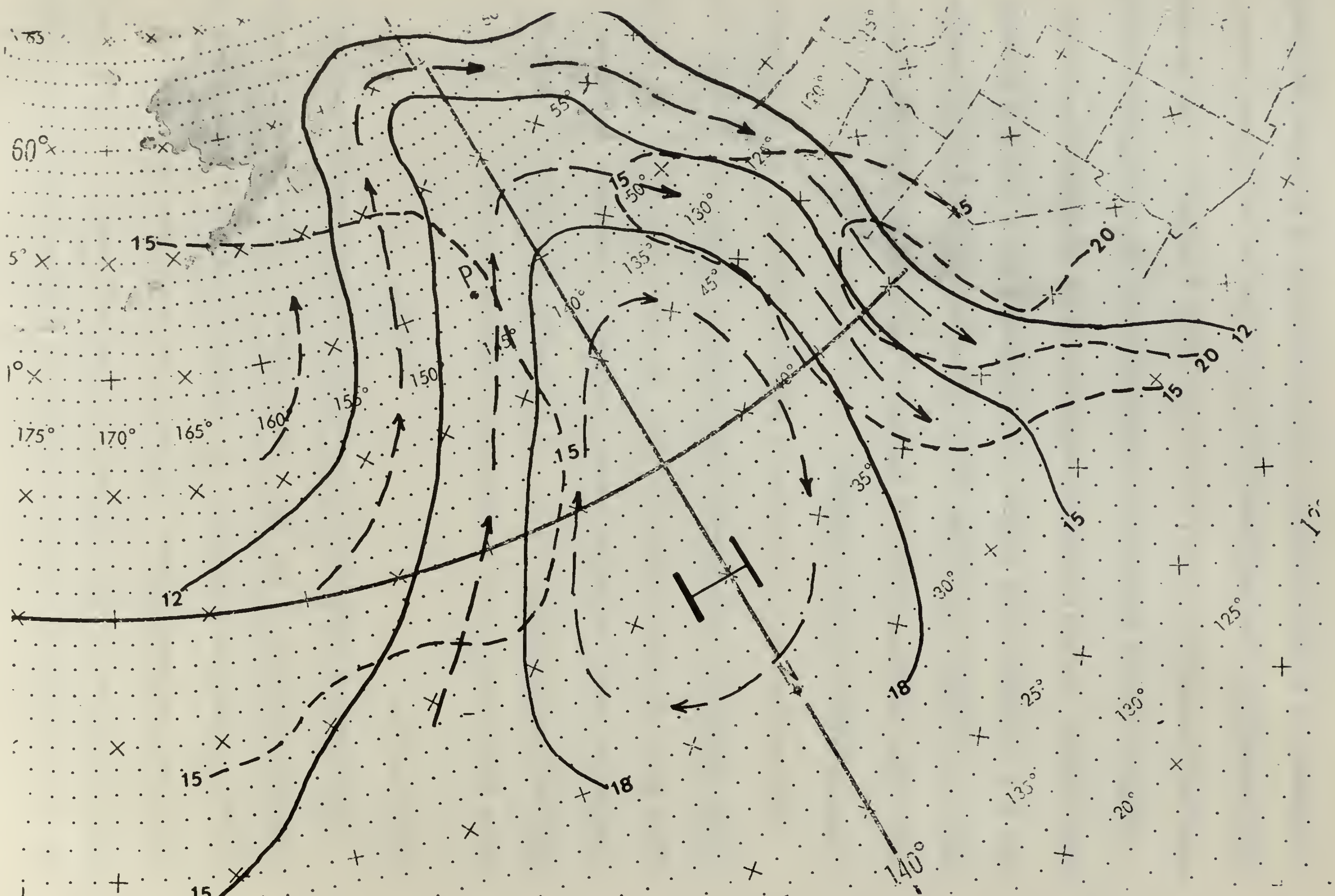

Figure 3a. June 1000mb heights(tens of meters) and isotachs(kts) showing derivation of wind direction arrows.

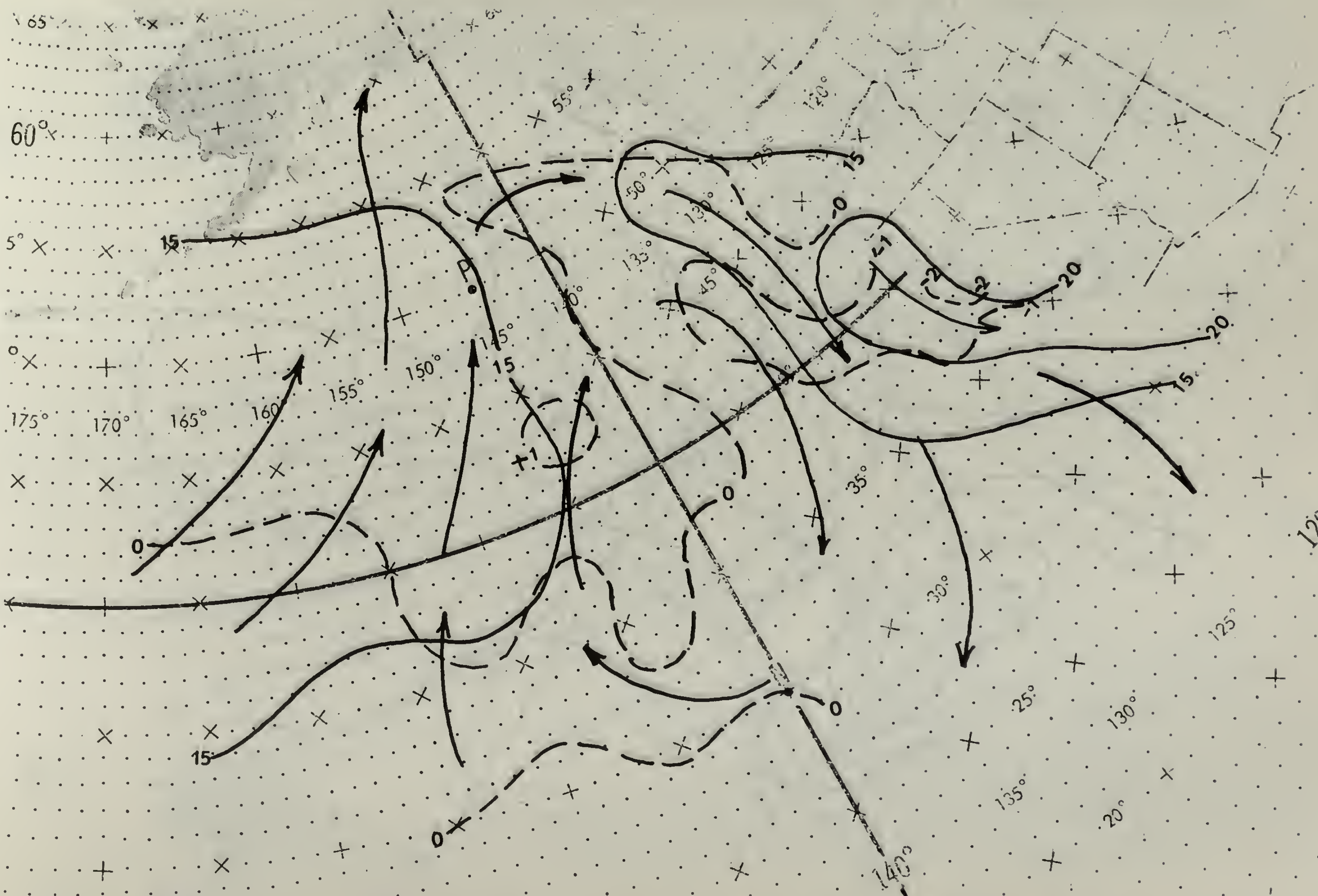

Figure 3b. June 1000mb isotachs(solid) and wind direction and SST anomaly(dashed).

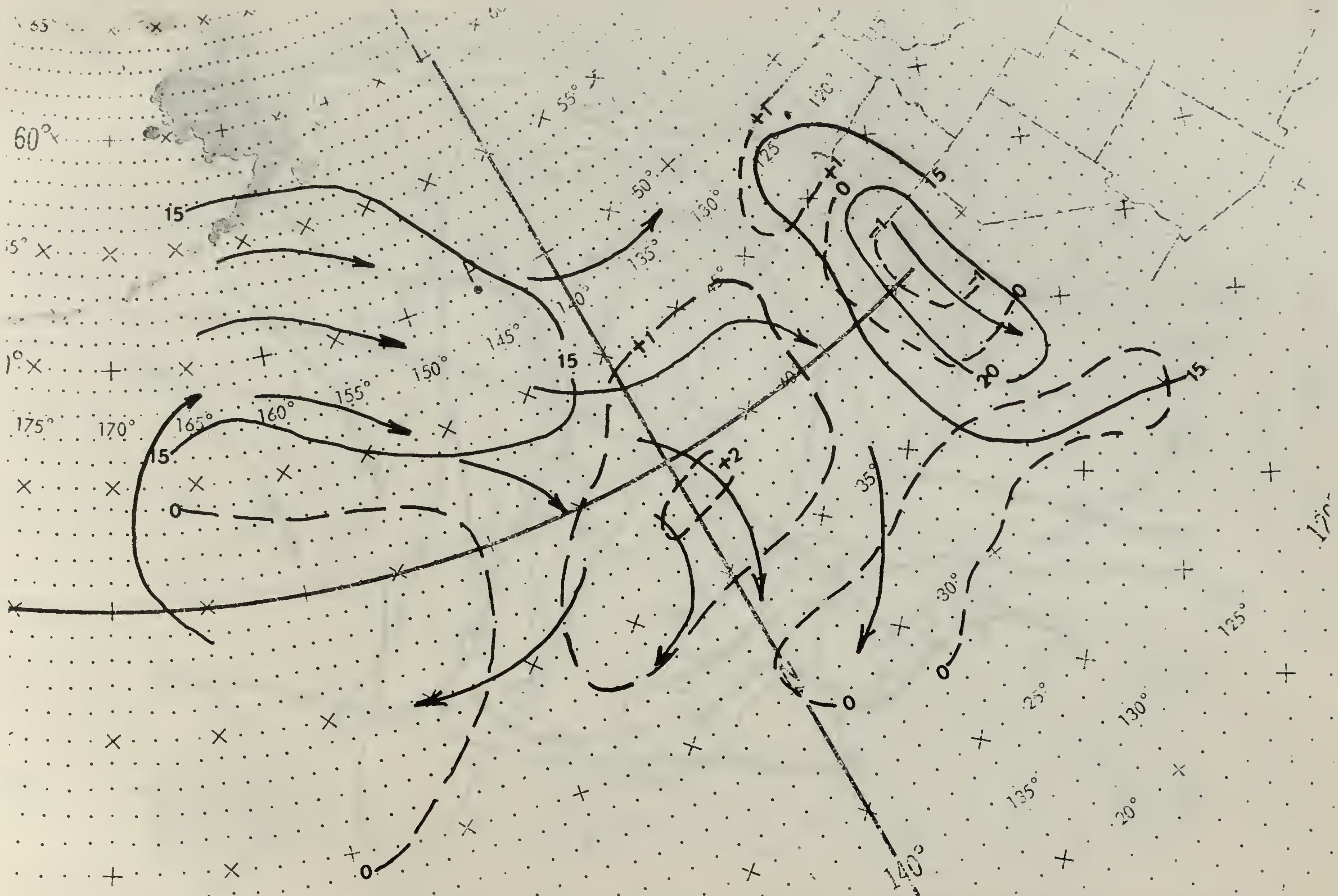

Figure 3c. July 1000mb isotachs(solid) and winds and SST anomaly(^{O}C, dashed).

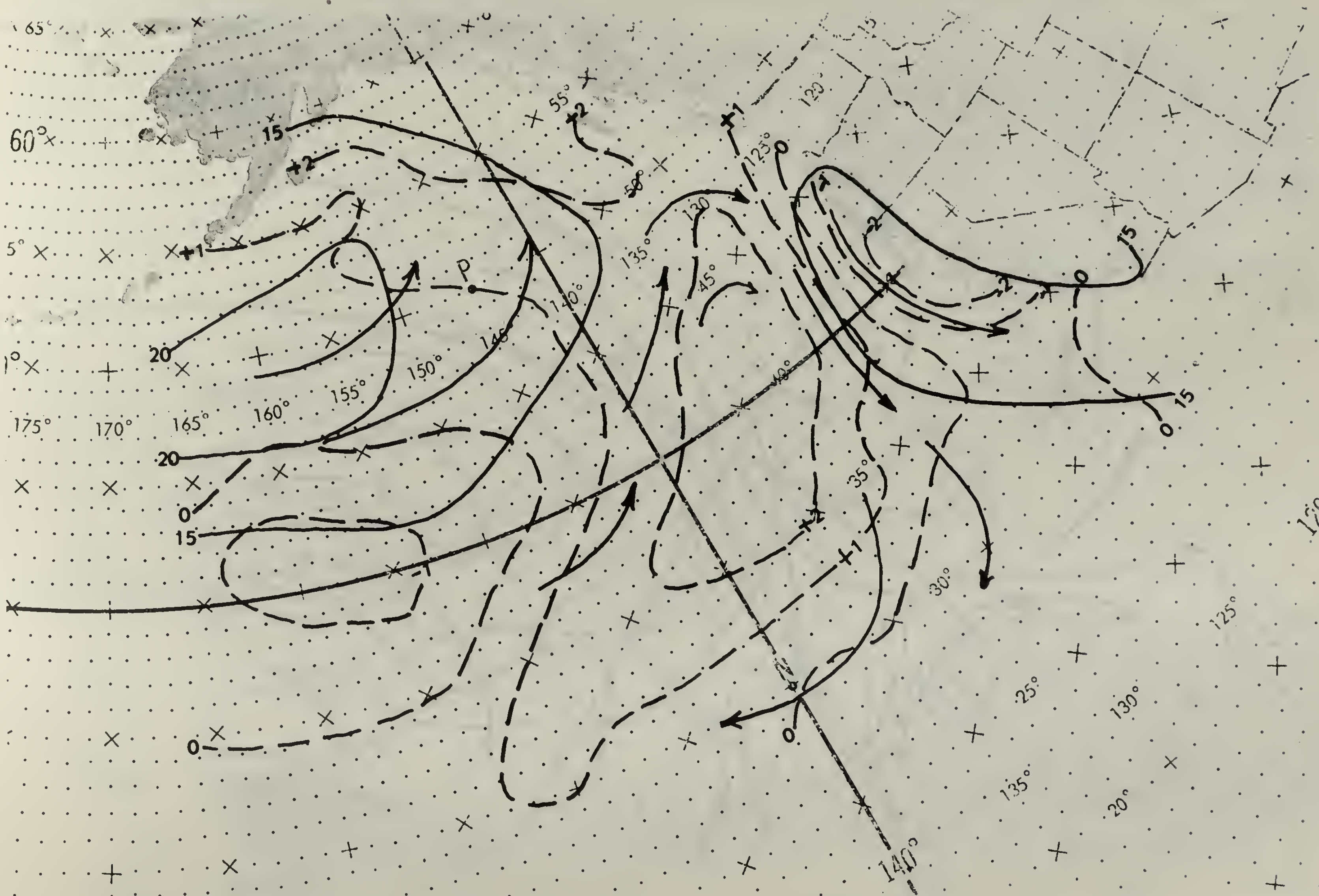

Figure 3d. August 1000mb isotachs(solid) and wind direction and SST anomaly(^{O}C, dashed)

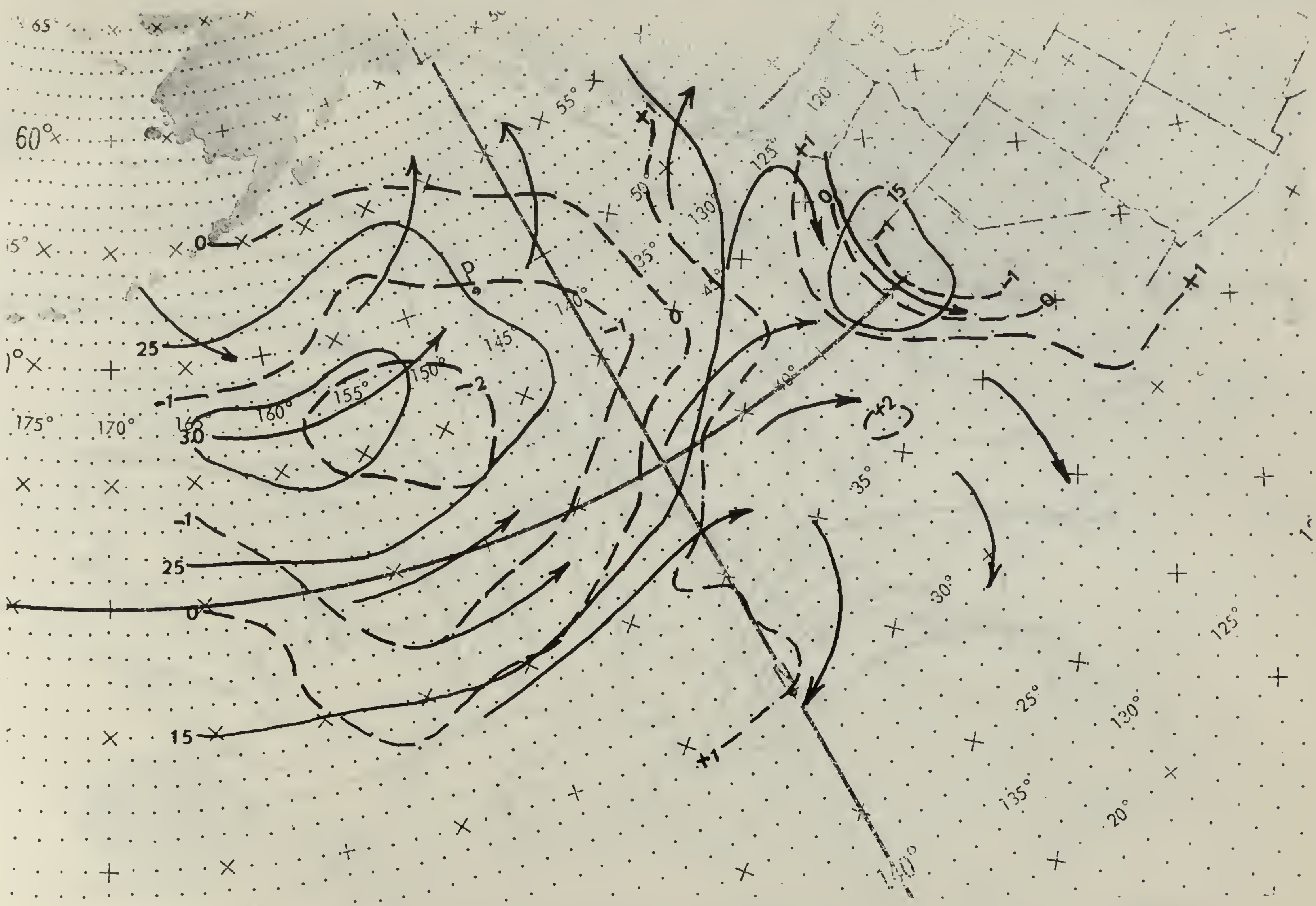

Figure 3e. September 1000mb isotachs(solid) and wind direction and SST anomaly(^{o}C, dashed).

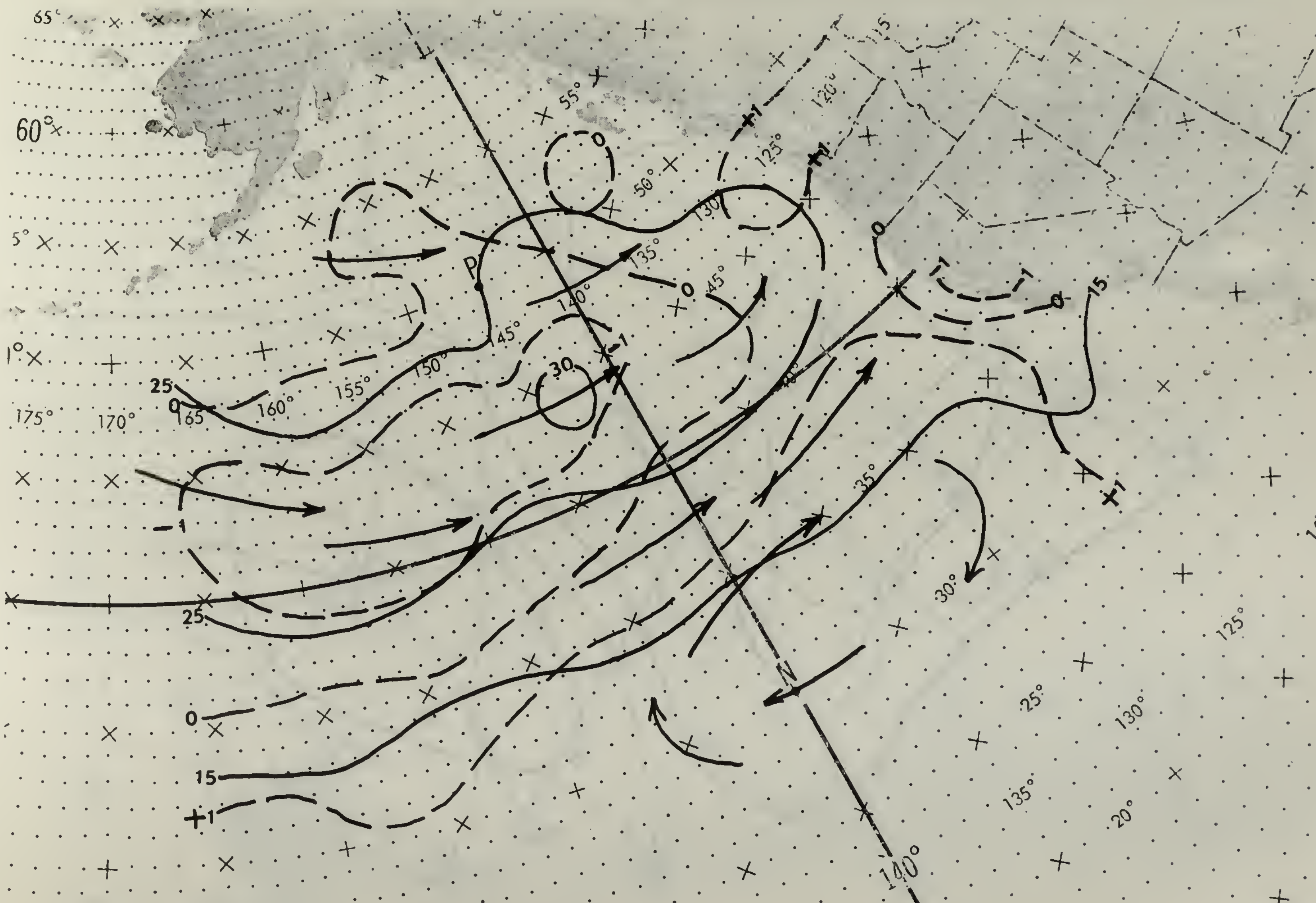

Figure 3f. October 1000mb isotachs(solid) and wind direction and SST anomaly(^{O}C, dashed).

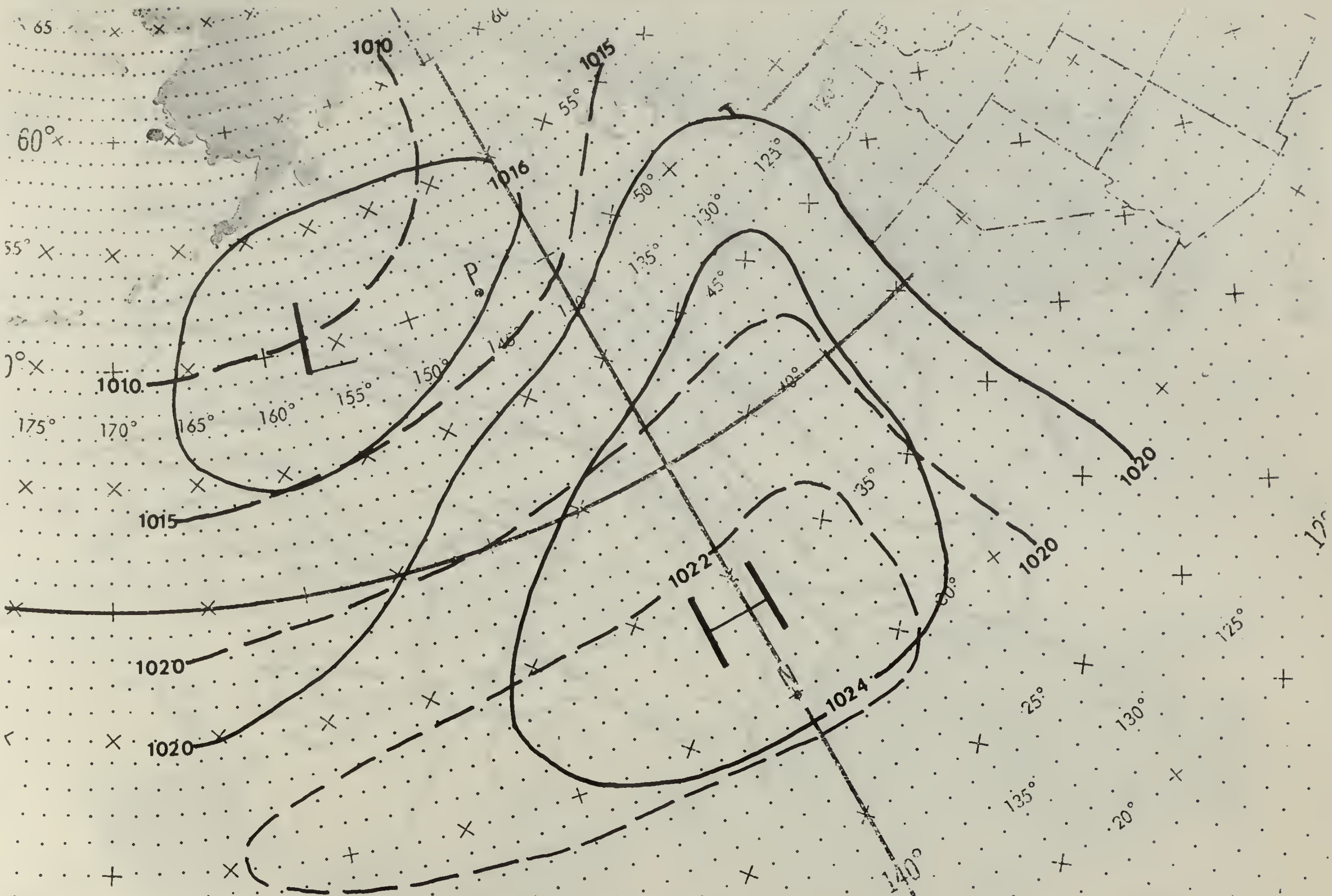

Figure 4a. May 1967 surface pressure(solid) versus long term mean surface pressure for May.

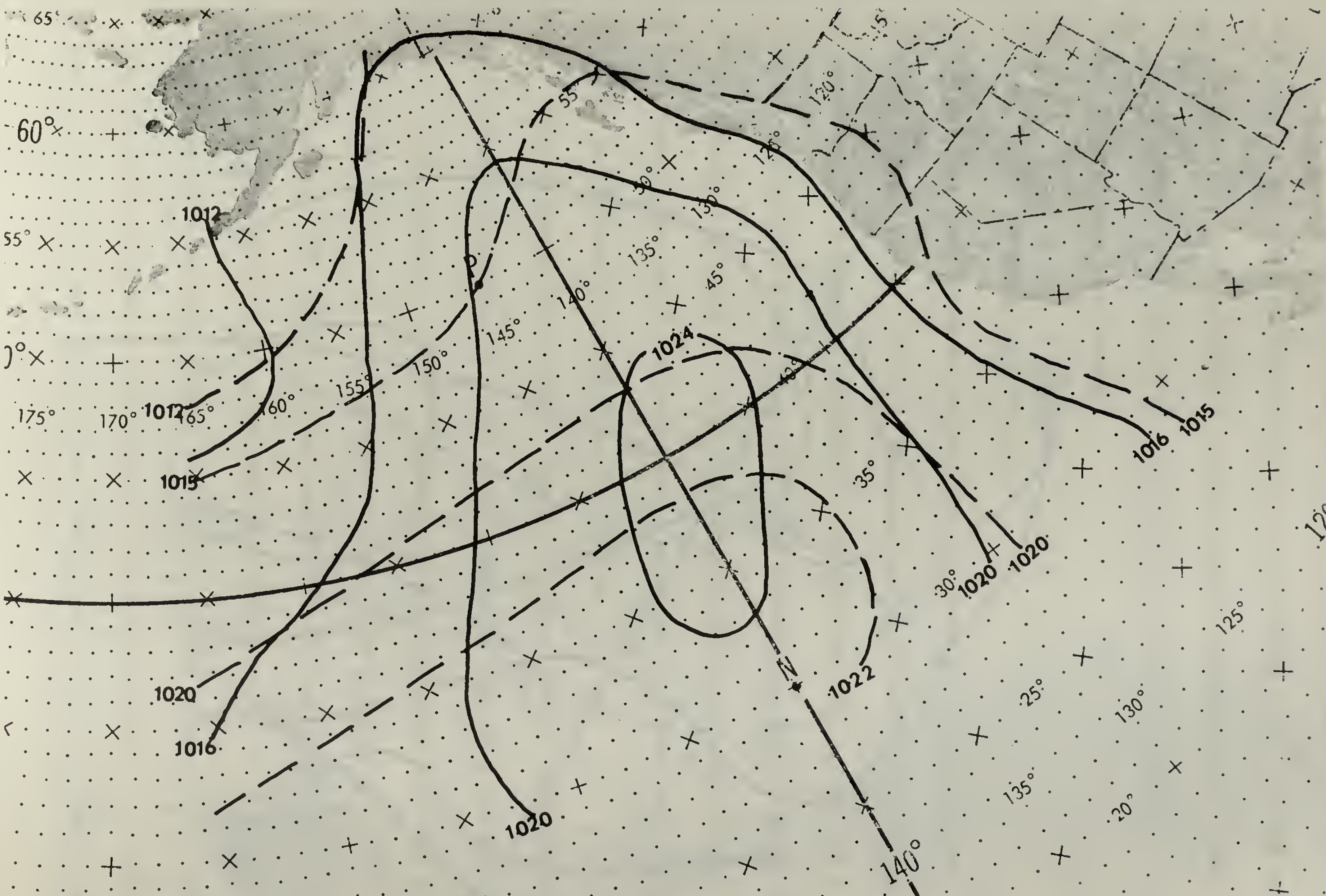

Figure 4b. June 1967 surface pressure(solid) versus long term mean surface pressure for June.

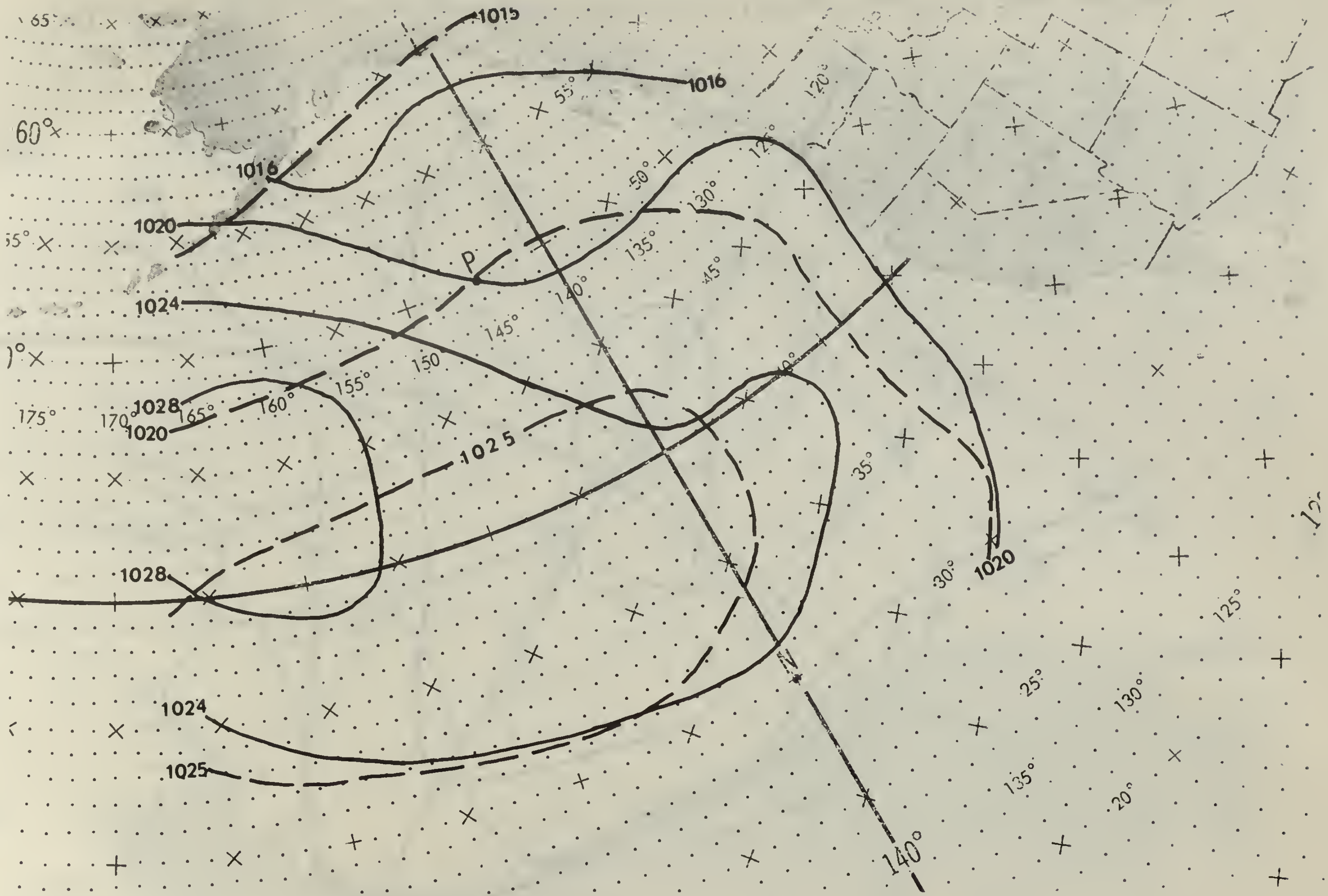

Figure 4c. July 1967 surface pressure(solid) versus long term mean surface pressure for July.

than normal in the area where the anomaly first became evident (see Figure 2a). During June (Fig. 4b) advection was considerably more southerly (by about 55°) than usual in the anomaly area. In July the situation (Fig. 4c) had almost reversed with advection from a more northerly direction than usual. After July the surface pressure distribution was near normal.

5.2.1 Lags Indicated by Advection

Another item becomes evident from inspection of these figures. There appears to be a lag of at least a month between advection and the response of surface temperature. The anomaly did not appear on 30-day mean charts until June, yet warm advection began in May. Also, the anomaly continued to increase in magnitude through late August even though advection was from a more northerly direction than normal in July and returned to near normal in August.

Further evidence of lags in response and the effects of advection can be seen by looking at 5-day mean charts for June (Fig. 5a-c). On the 10 June (5a) chart, winds were relatively strong and southerly in the region of 155 W. Also, a tongue of negative SST anomaly was centered near 49N 153W. On the next chart, 15 June, the negative area had been removed except in the area of 25+ knot winds of 10 June. The warm advection must have been sufficiently strong to counteract cooling due to wind mixing except in the area of maximum wind. The 15 and 20 June charts also show the effects of advection. On 15 June winds were

Figure 5a. 10 June 5-day mean 1000mb winds(solid) and SST anomaly(dashed).

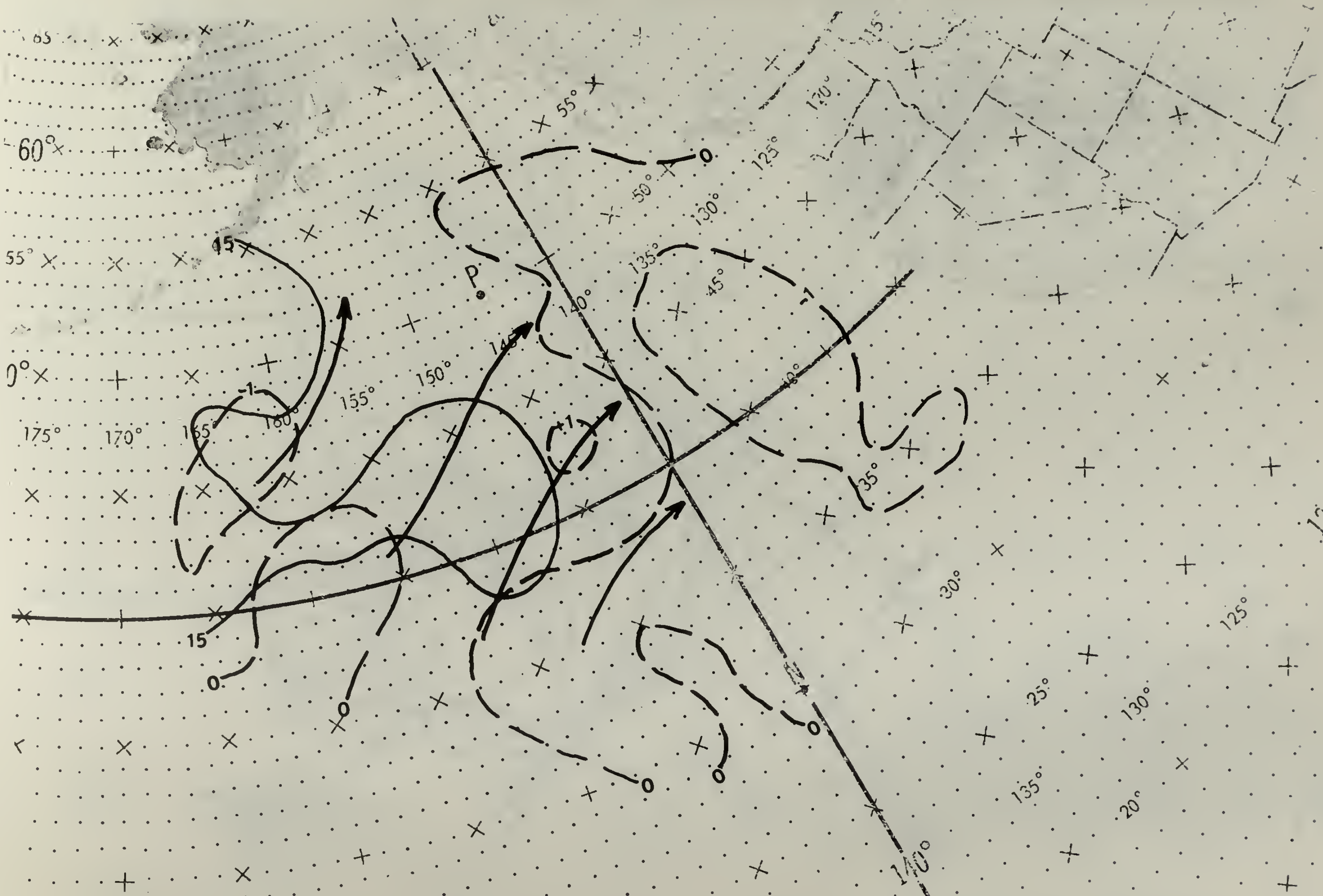

Figure 5b. 15 June 5-day mean 1000mb winds(solid) and SST anomaly(dashed).

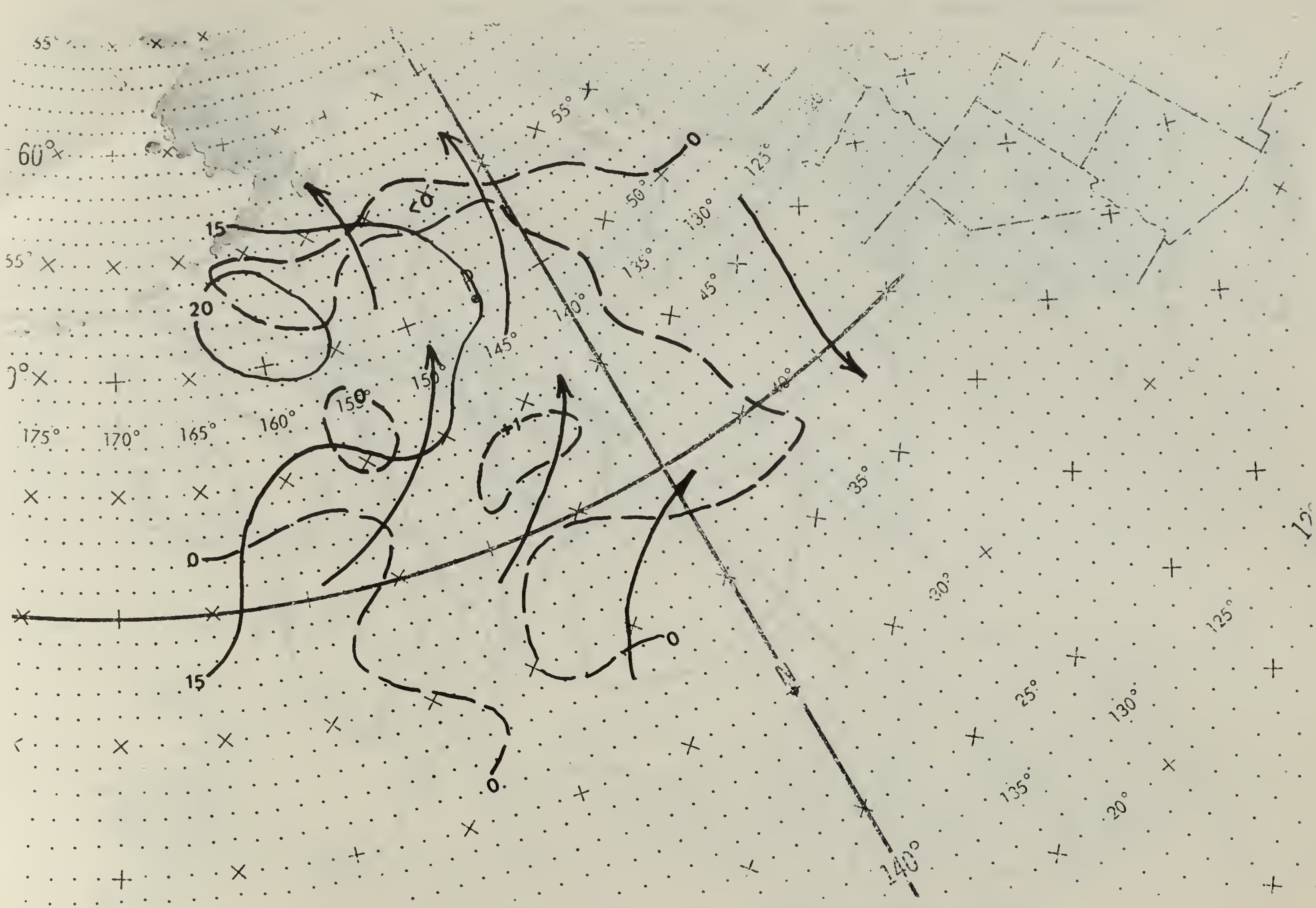

Figure 5c. 20 June 5-day mean 1000mb winds(solid) and SST anomaly(dashed).

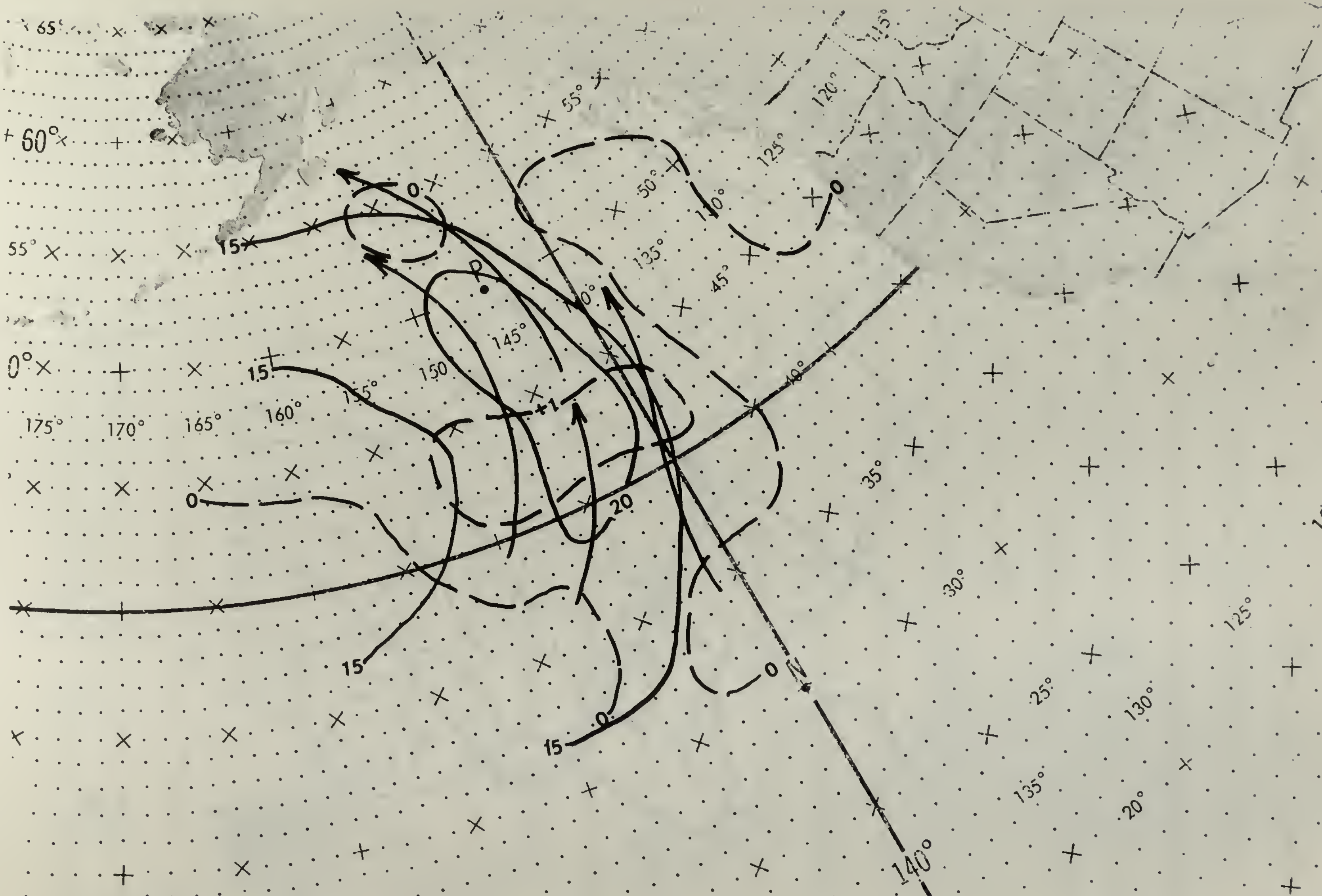

Figure 5d. 25June 5-day mean 1000mb winds(solid) and SST anomaly(dashed).

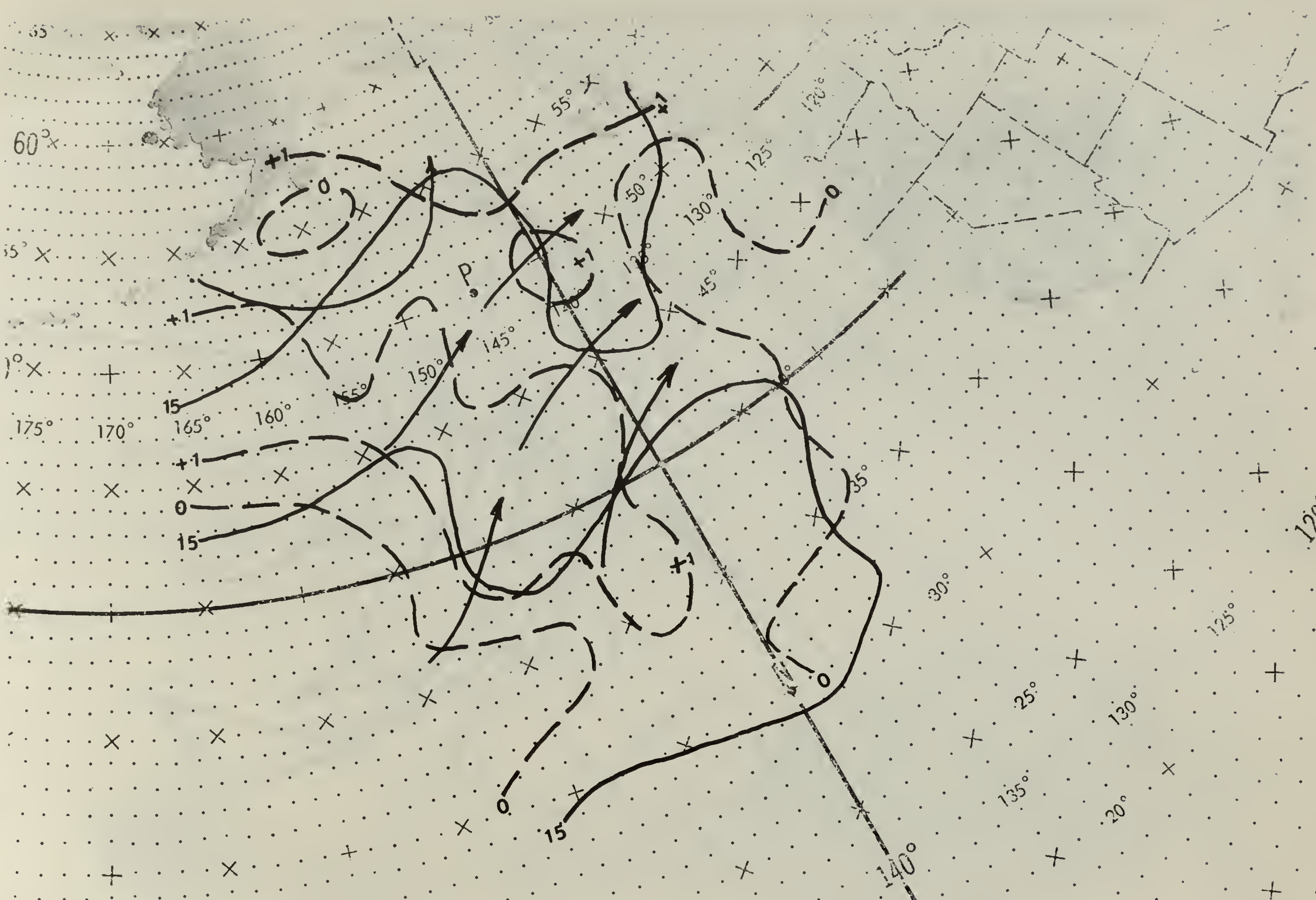

Figure 5e. 30 June 5-day mean 1000mb winds(solid) and SST anomaly(dashed).

SW and the zero anomaly isopleth lay roughly along the 140W meridian. By 20 June, the zero isopleth had moved in the direction of the 15 June winds. The lag in response of the surface water to advected warmer water is also evident in the northern portion of the region studied.

On 20 June (Fig. 5c), a tongue of cool water extended across the Gulf of Alaska. In the same area southerly winds existed. By 25 June (Fig. 5d) the tongue had broken off indicating increasing SST in the north five days after the advection from the south.

From 25 to 30 June, the small negative anomaly in the Gulf of Alaska moved to the northwest in the direction of the 25 June winds. Further inspection of the June 5-day charts shows definite evidence of warming due to advection of surface waters and lags in response of surface waters to this advection.

Support of the advection argument shows up on the 5-day mean SST charts for June (Figs. 6a-c). The 10 June chart shows a curvature of isotherms to the north just west of 140W in the general area of the anomaly (and the southerly winds), indicating a northward movement of warm water. Similar patterns in the anomaly area appear in the 25 and 30 June SST charts.

An interesting comparison of the effects of mixing versus advection can be seen in Figure 1. During June when the winds were lightest (15 and 20 June) the magnitude of the anomaly actually decreased, while during the periods of strongest wind, 10, 25 and 30 June, (with increased mixing) the magnitude of the (positive) anomaly increased. The increase

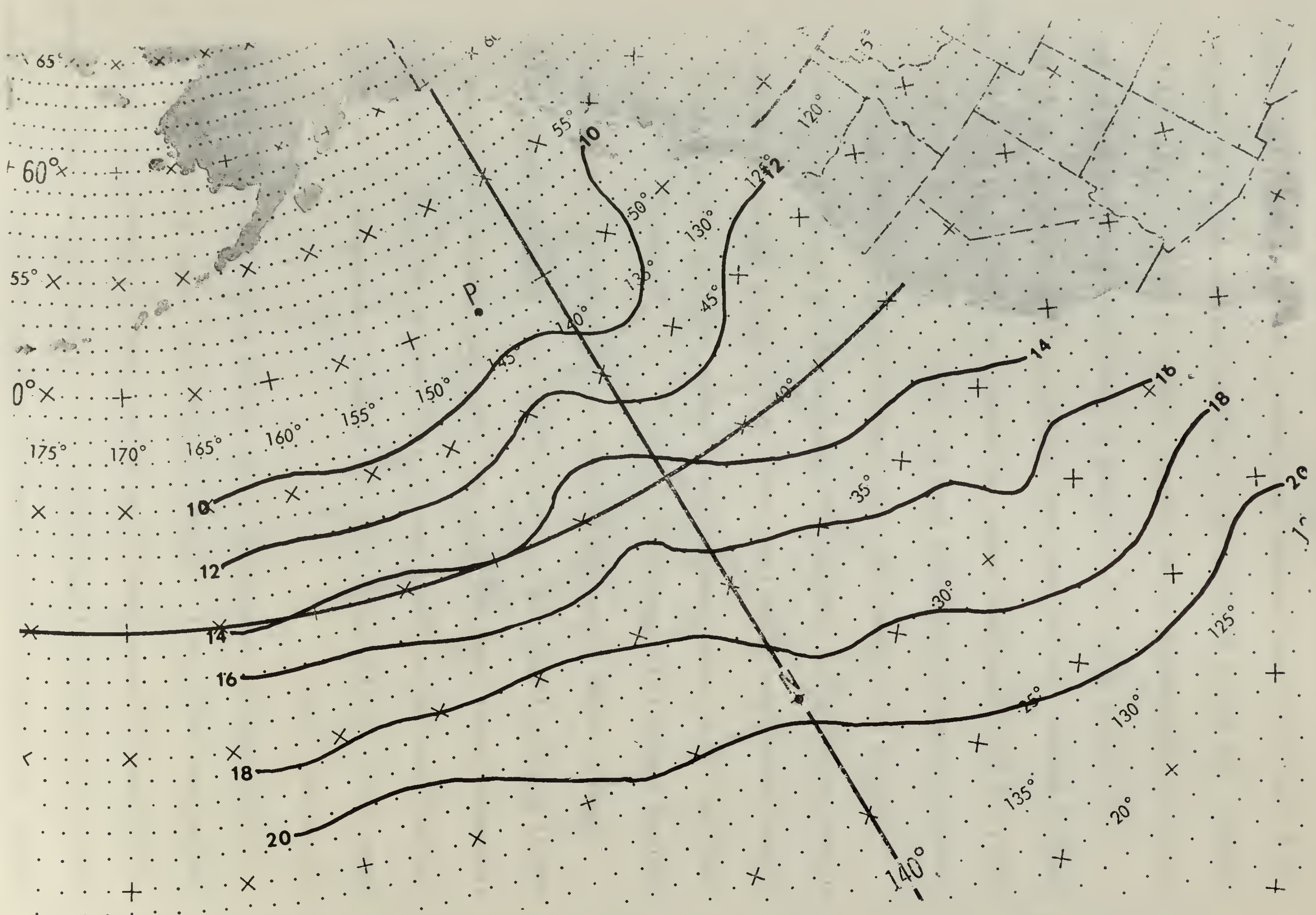

Figure 6a. 10 June 5-day mean SST.

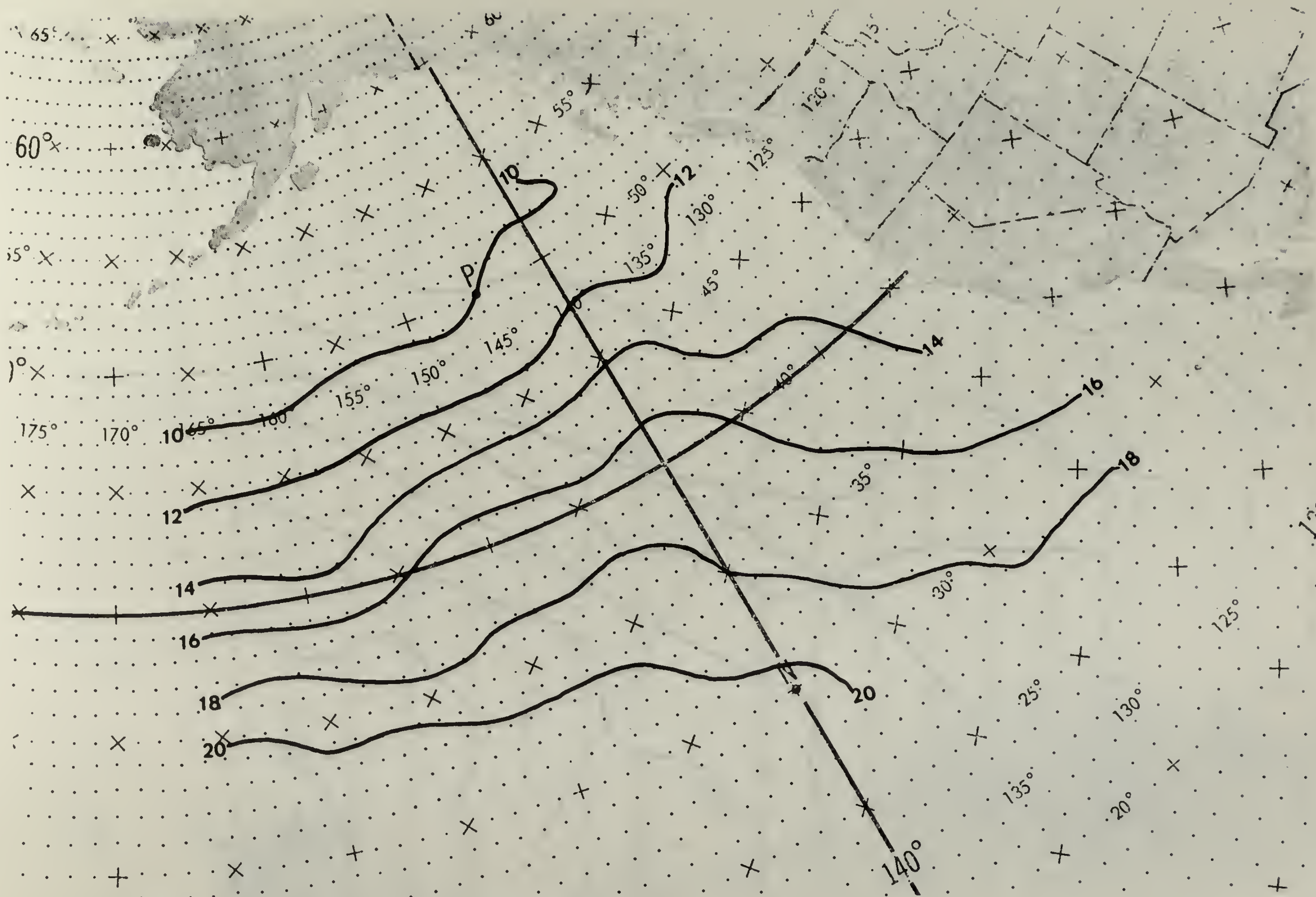

Figure 6b. 25 June 5-day mean SST.

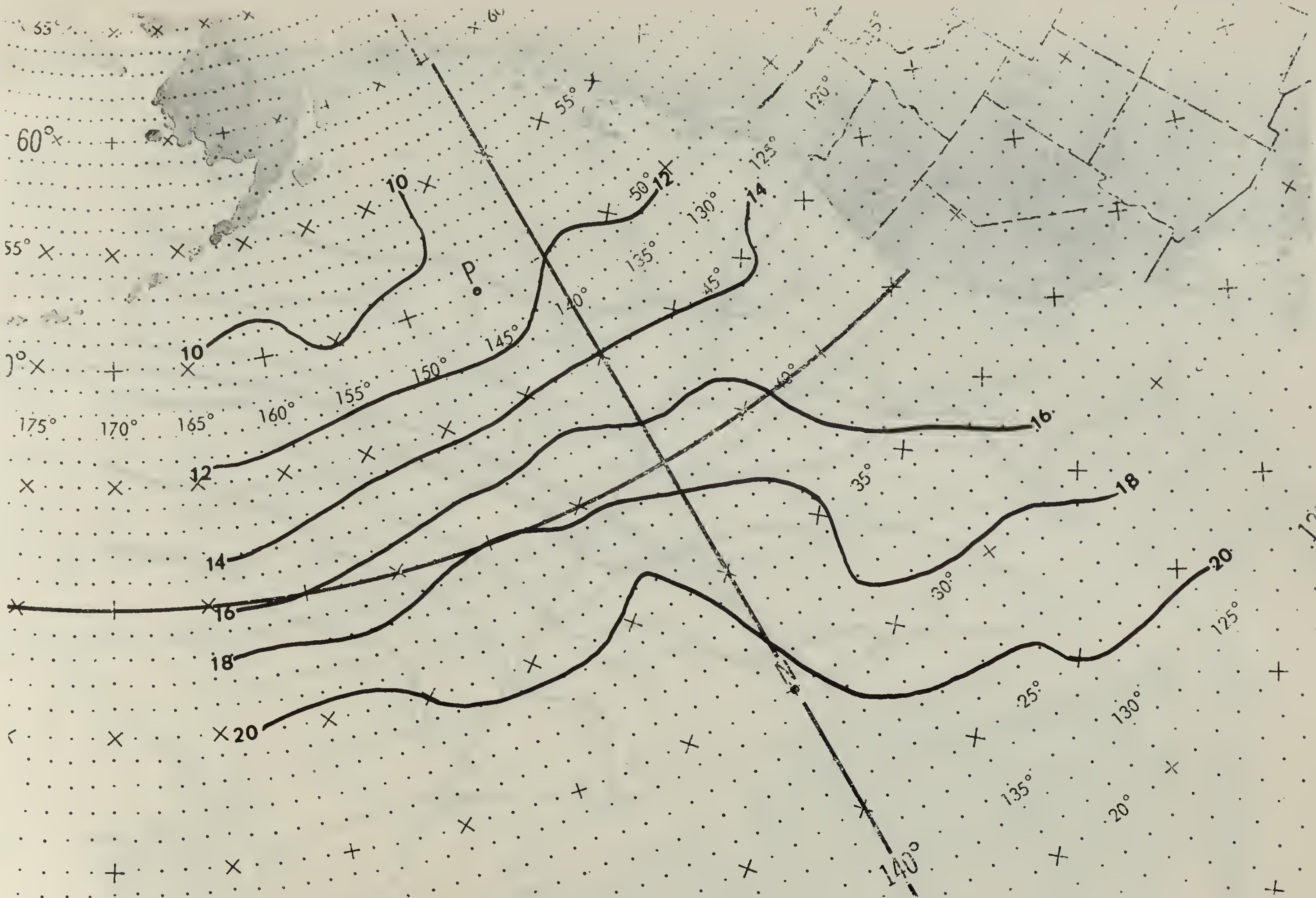

Figure 6c. 30 June 5-day mean SST.

is probably due to the fact that in each case the strong winds were from the south, bringing in sufficient warm water by advection to overcompensate the cooling effects of mixing.

5.3 Mixed Layer Depth

Shallow mixed-layer depths show a strong correlation with the positive SST anomaly. In Figures 7a-e, which compare monthly mean MLD's with SST anomalies, each month except October shows the positive anomaly to be in the area of shallowest MLD's. The negative SST anomaly which formed to the west in July and August was in the region of deepest MLD's. The negative SST anomaly off southern California in June, July and August also coincided with an area of relatively deep MLD.

These correlations are reasonable because the MLD in summer should be directly related to surface winds. Strong winds will produce a deeper MLD, more mixing, and cooler water temperatures.

The fact that a region of shallow MLD exists is not <u>by itself</u> sufficient to cause formation of a SST anomaly. Other parameters which determine the heat content of the surface layer must be acting also to warm the shallow water layer. On the other hand, a relatively deep MLD probably will inhibit anomalous warming of the thick surface layer because of the great amount of heat required.

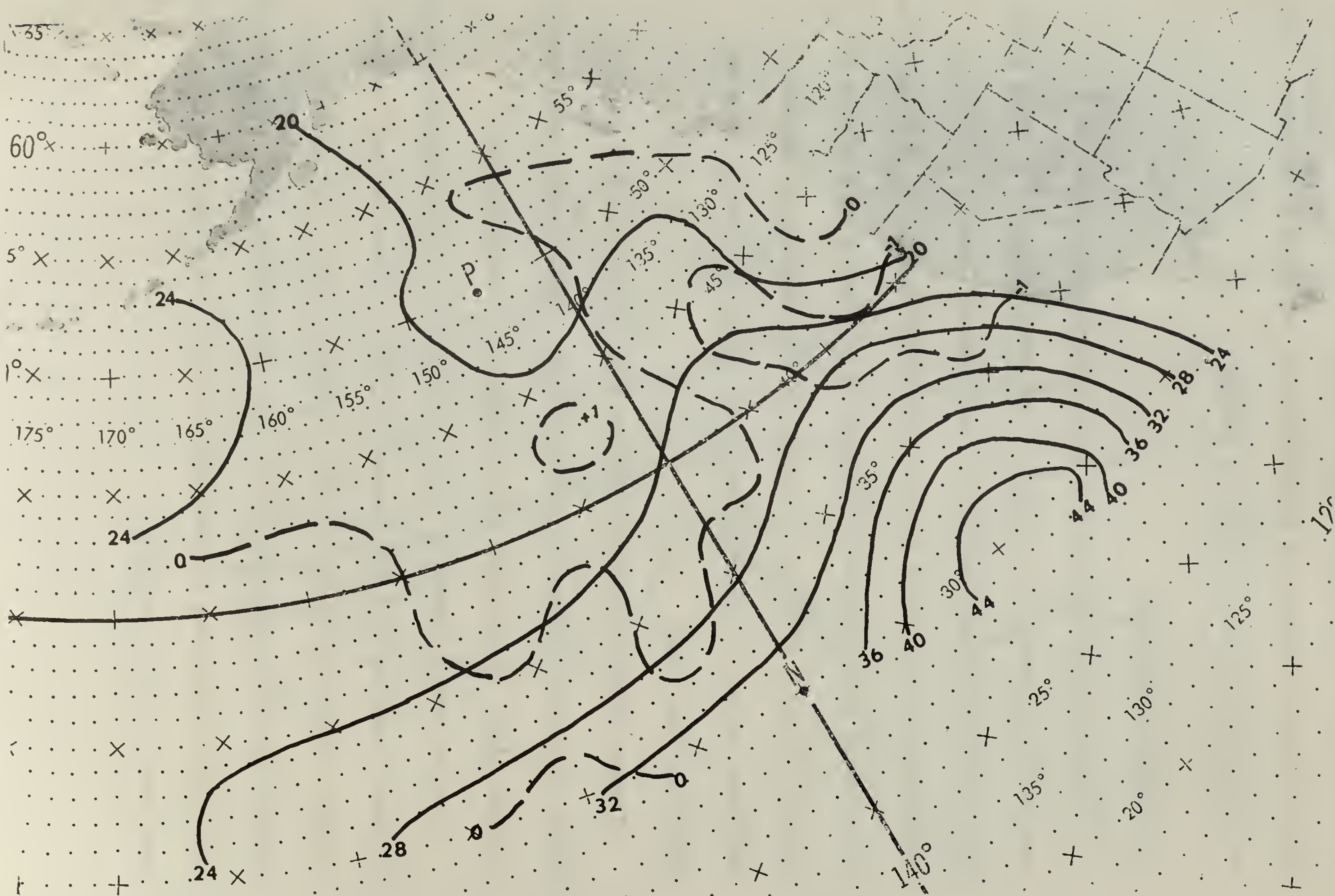

Figure 7a. June mean MLD(solid) and SST anomaly(dashed).
(m)

Figure 7b. July mean MLD (m) (solid) and SST anomaly (dashed).

Figure 7c. August mean MLD (m) (solid) and SST anomaly (dashed).

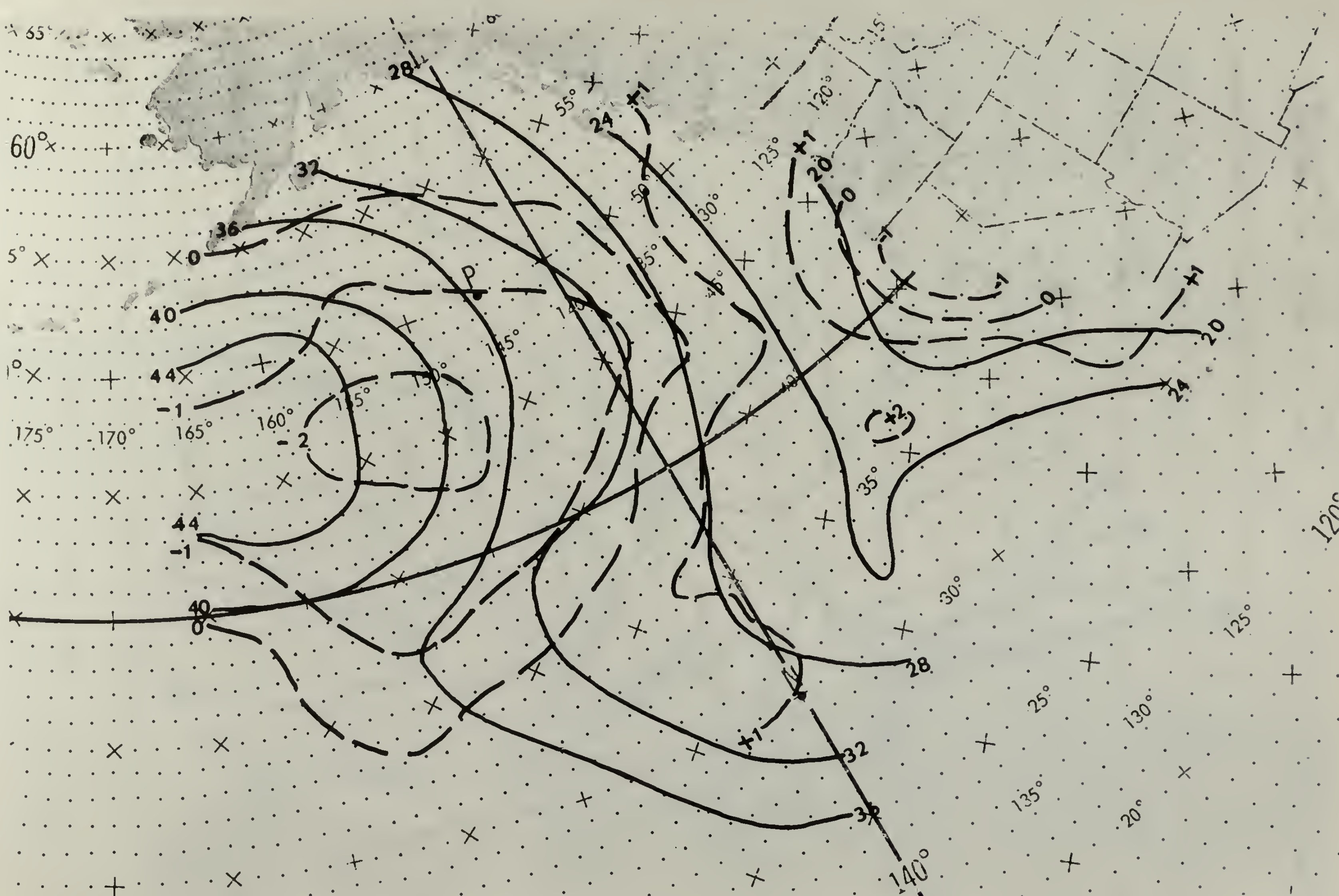

Figure 7d. September mean MLD (m) (solid) and SST anomaly (dashed).

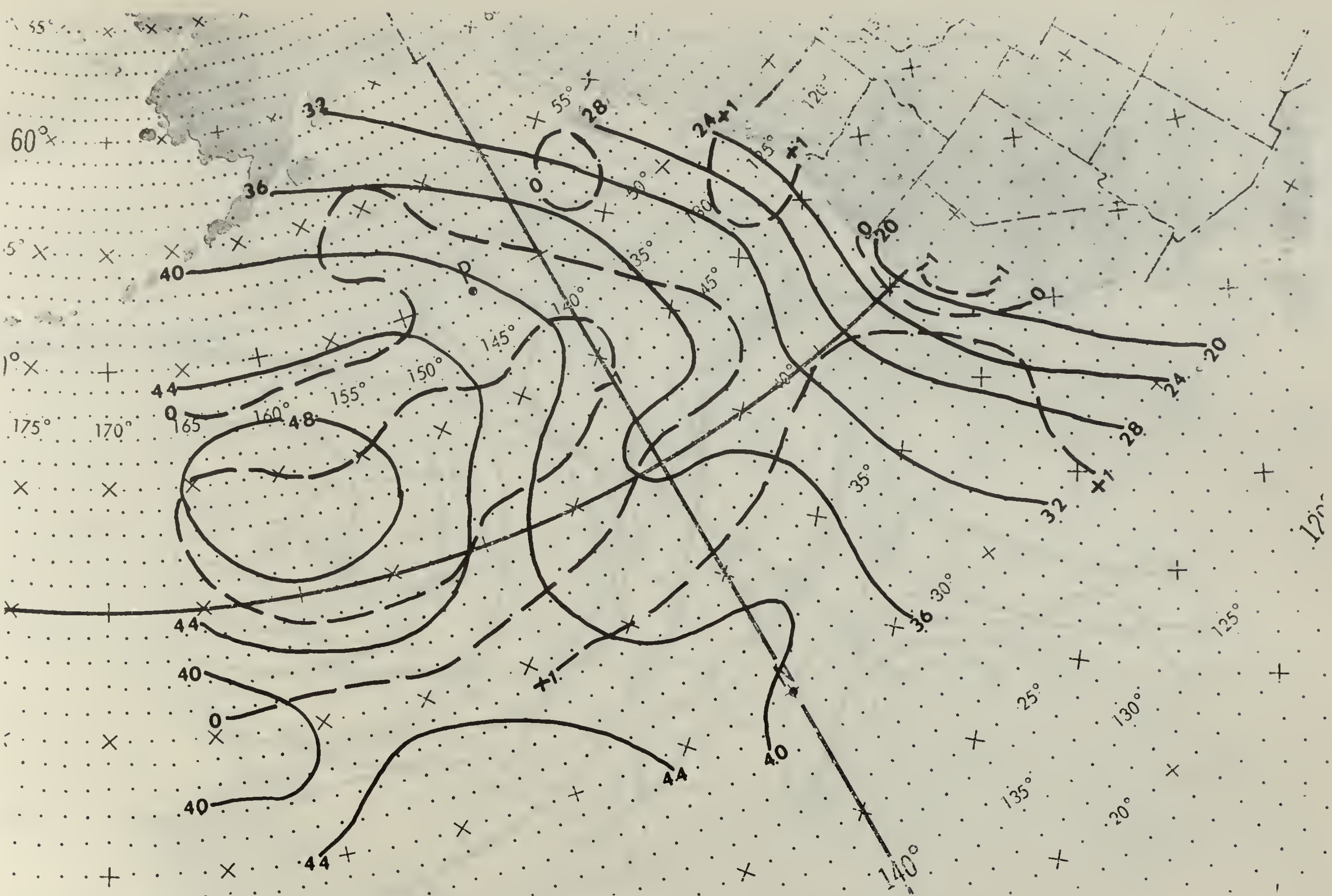

Figure 7e. October mean MLD(solid) and SSI anomaly(dashed).
(m)

5.4 Net Heat Exchange and Lag Effects

Net heat exchange, Q_n, across the air-sea interface is ultimately responsible for most of the heat energy entering the ocean in regions away from strong currents. In this study, as also reported by Hanzawa (1962), the SST anomaly was associated with regions of high Q_n (see Fig. 8a-e). The maximum values of Q_n occurred in May, June and July, the period during which the anomaly was increasing in magnitude and areal extent. In the anomaly region, Q_n reached its seasonal maximum value in June and decreased steadily thereafter. As the SST anomaly continued to increase in magnitude through August, either (1) other parameters influenced the anomaly, (2) there was a lag in response of surface layers of water to Q_n, or (3) both (1) and (2) occurred. High values of Q_n alone are not enough to cause anomalous SST's (to be shown in Section 6). It appears there is a lag in response to Q_n as is shown by the continued increasing magnitude of the anomaly two months after Q_n had reached its maximum value.

Further evidence of a lag of about a month can be derived from Figure 1. In May and July, Q_n values were about equal in the region of the anomaly (320-360 $\frac{\text{g-cal}}{\text{cm}^2\text{-day}}$). Inspection of the slope of increasing magnitude of the anomaly (Fig. 1) in June and August shows them to be about the same. Thus, the rates of increase in the magnitude of the anomaly were equal one month after periods with equal values of Q_n. In June, Q_n was considerably higher (380-455 $\frac{\text{g-cal}}{\text{cm}^2\text{-day}}$) than in May and July. One month later, in July, the slope of increasing

anomaly magnitude was also greater. Thus, for three consecutive months lags in response to Q_n were indicated. Figure 1 indicates that the rate of increase in SST is proportional to Q_n.

The program used by FNWF for calculating Q_n has been in use for only about three years, therefore valid long-term means are not available for comparison with the 1967 values. The significant thing here is the sequence of amounts of heat exchange. The highest values of Q_n were at the onset of the anomaly and then they decreased through October, whereas the magnitude of the anomaly increased through August, two months after Q_n began to decline. Thus, while heat exchange apparently made a significant contribution to generation and early development, the anomalous heating of the surface waters continued on through the period while Q_n was decreasing. One can conclude that both response lags and other parameters influenced the growth of the anomaly.

An interesting sidelight was found during this part of the study. The Bureau of Commercial Fisheries, La Jolla (BCF) computes monthly mean values of Q_n along with several other parameters. Comparison of Q_n values compiled by FNWF and the Bureau of Commercial Fisheries (1967) shows considerable differences. FNWF values were consistently higher, with values of maximum Q_n often more than twice those of BCF. Although values varied, the areas of relative maxima and minima compared favorably. A brief comparison of the two sets of equations can be found in the appendix.

Figure 8a. May mean net heat exchange($\frac{g\text{-cal}}{cm^2\text{-day}}$, solid) and SST anomaly(dashed).

Figure 8b. June mean net heat exchange($\frac{\text{g-CAL}}{\text{CM}^2\text{-DAY}}$, solid) and SST anomaly(dashed).

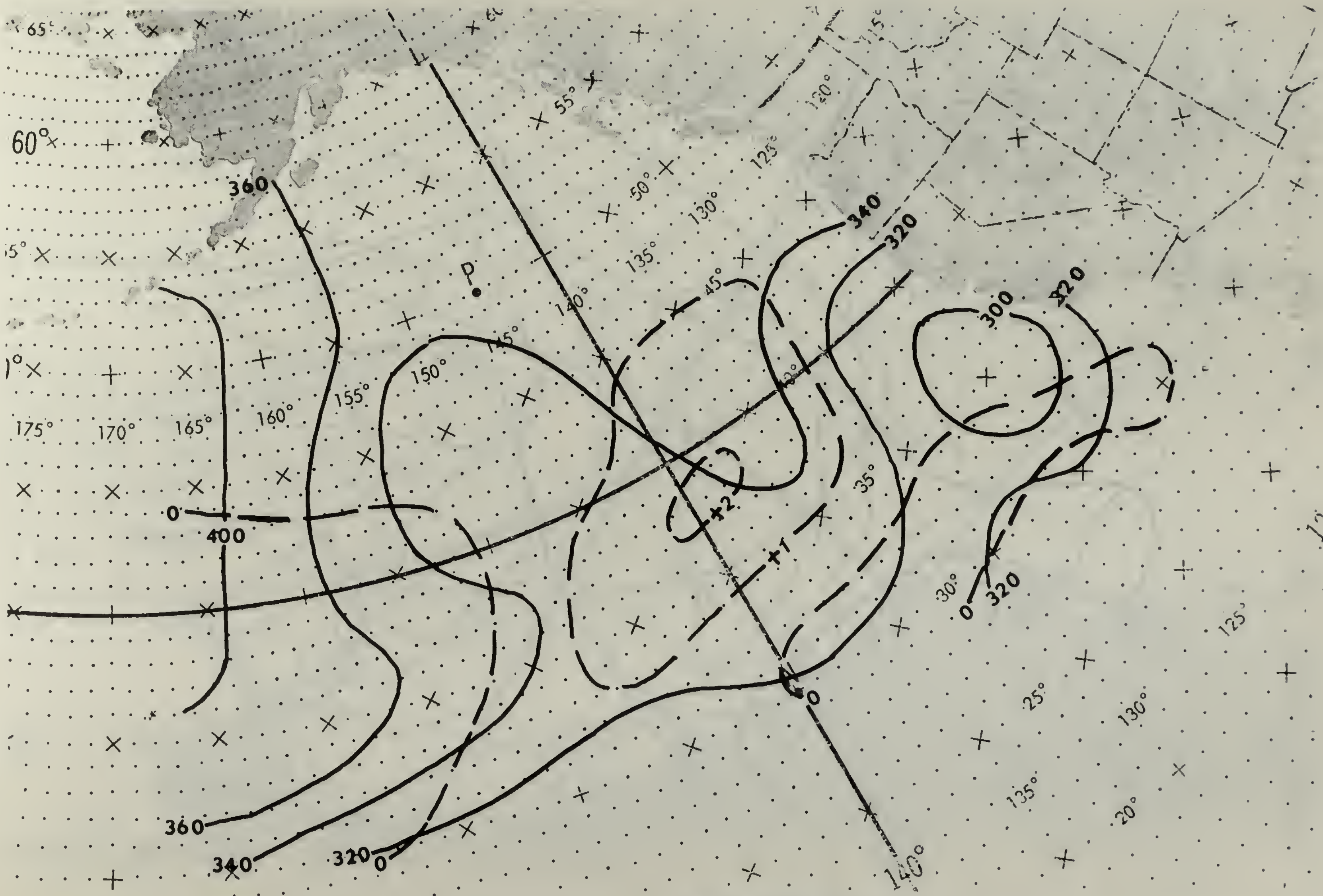

Figure 8c. July mean net heat exchange($\frac{\text{g-CAL}}{\text{CM}^2\text{-DAY}}$, solid) and SST anomaly(dashed).

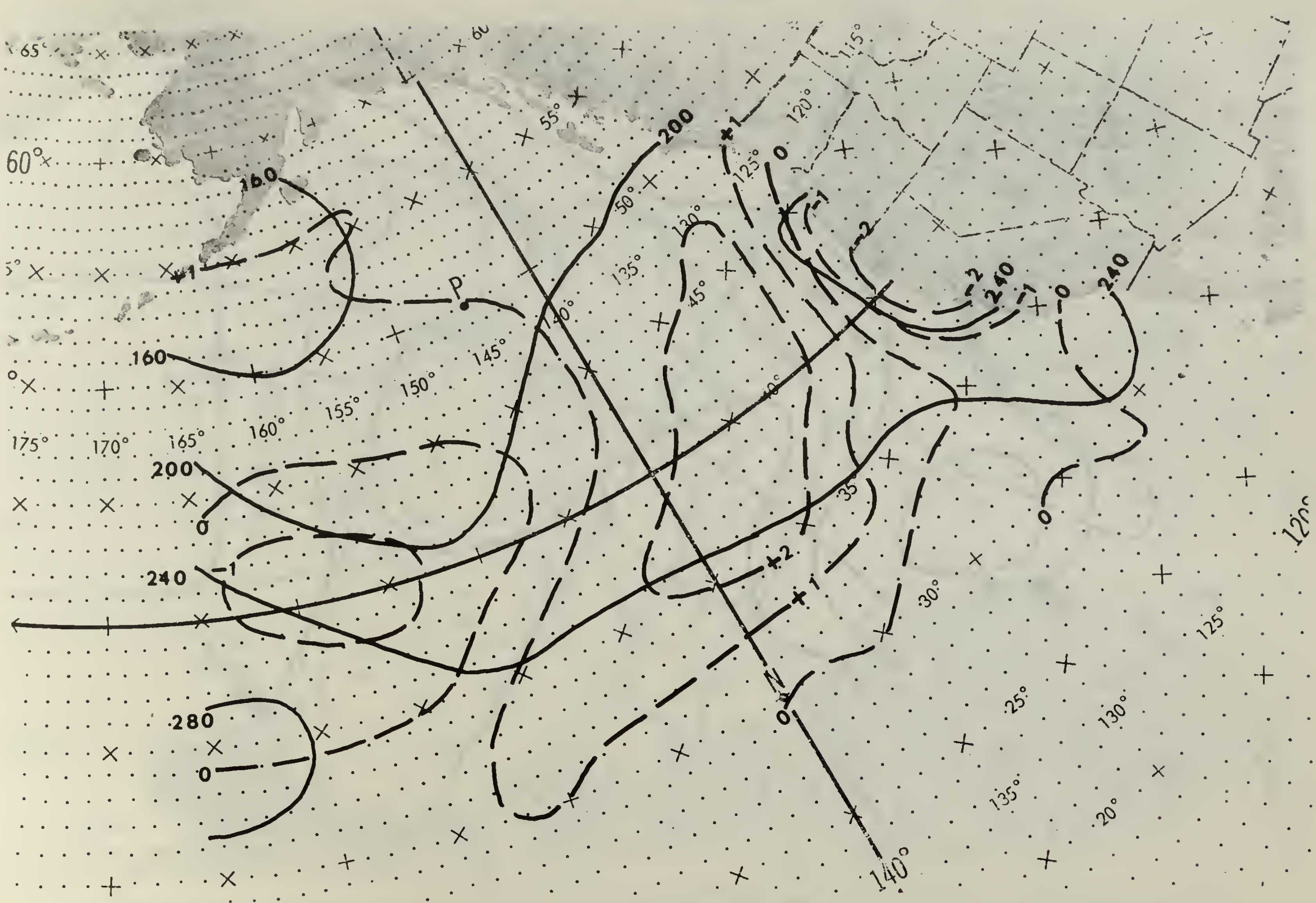

Figure 8d. August mean net heat exchange($\frac{g\text{-CAL}}{CM^2\text{-DAY}}$, solid) and SST anomaly(dashed).

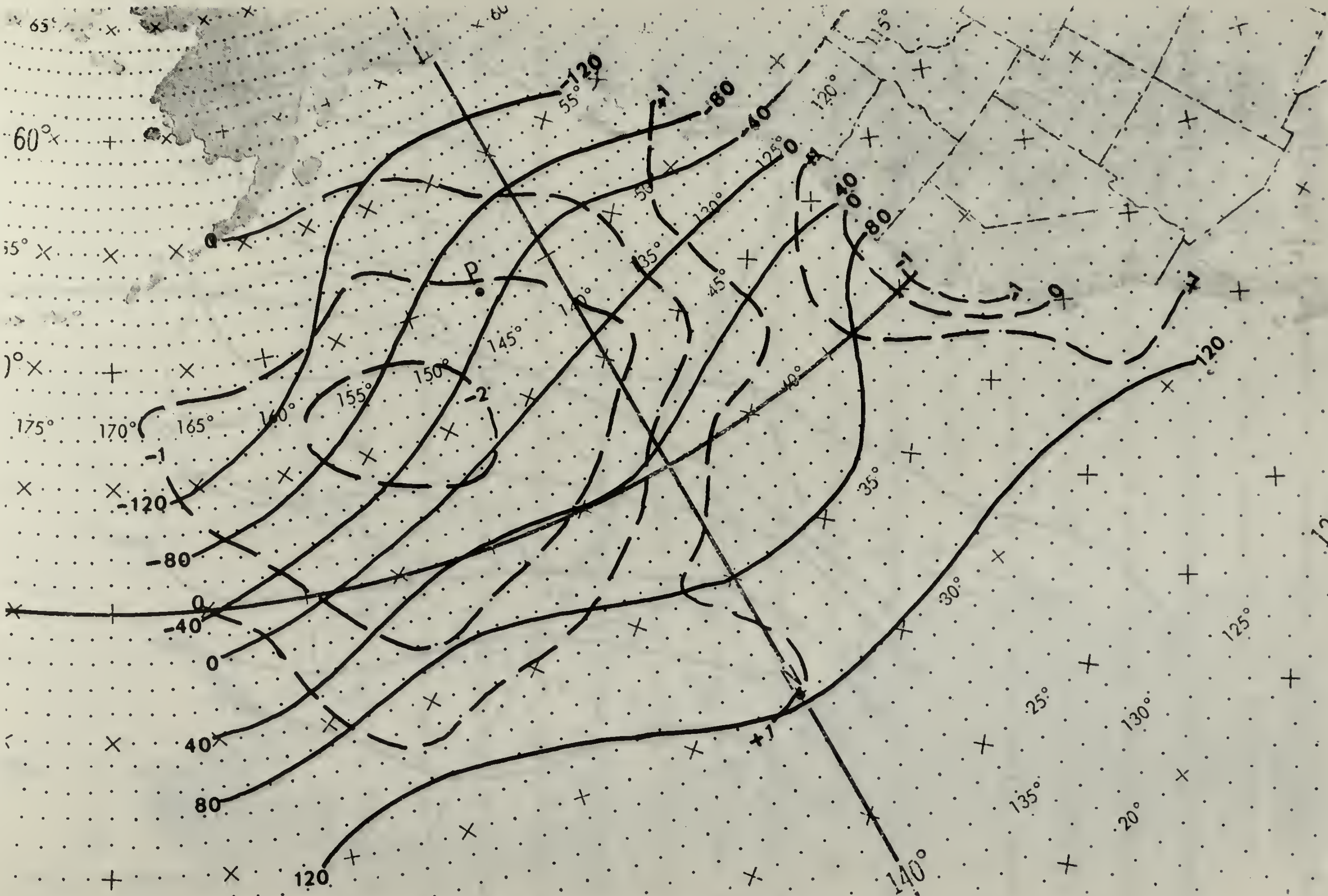

Figure 8e. September mean net heat exchange($\frac{g\text{-}CAL}{CM^2\text{-}DAY}$, solid) and SST anomaly(dashed).

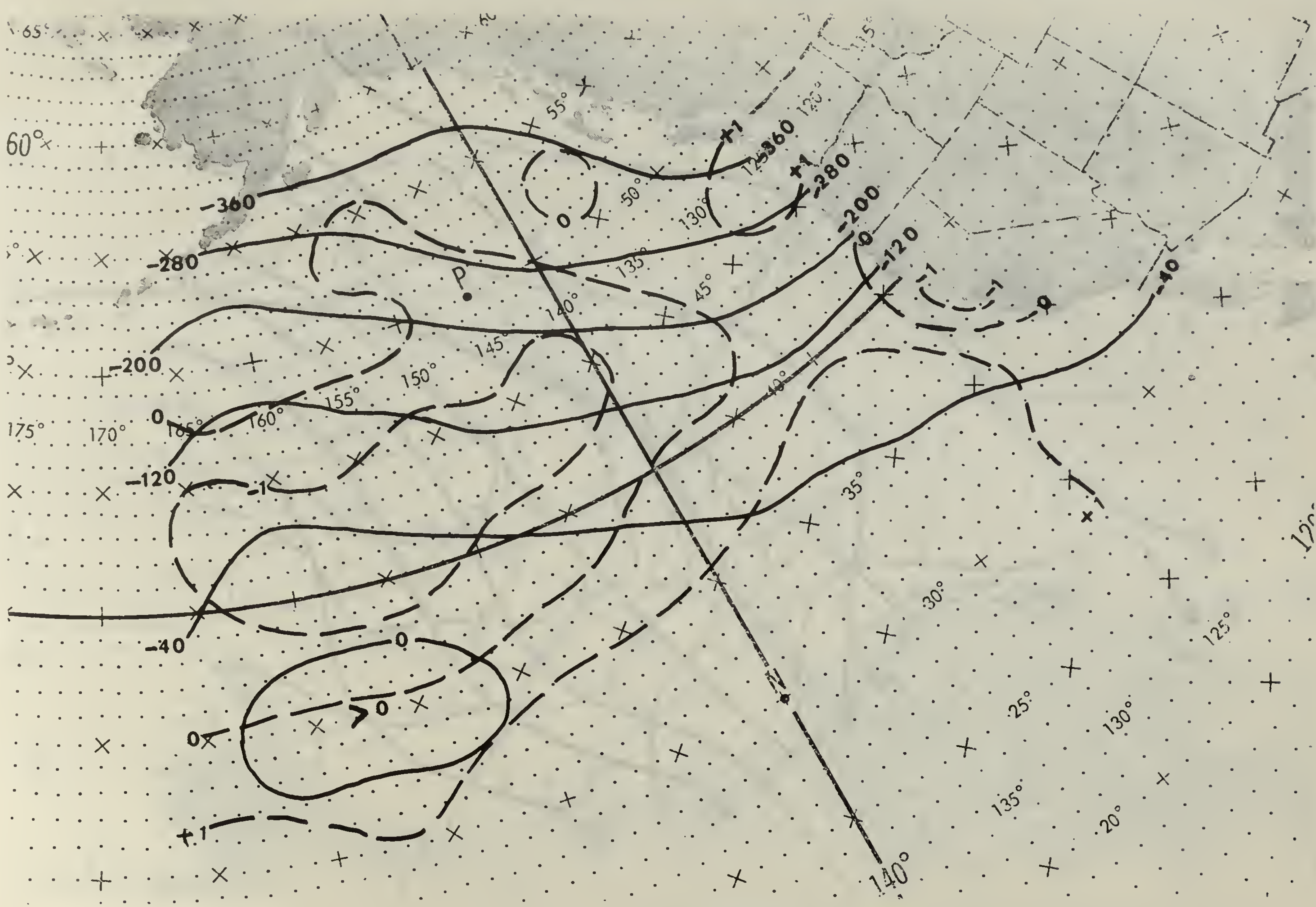

Figure 8f. October mean net heat exchange$\left(\frac{\text{g-CAL}}{\text{CM}^2\text{-DAY}}\right.$ solid) and SST anomaly(dashed).

5.5 Convergence and Divergence Effects

Horizontal convergence and divergence can have an appreciable influence on heating or cooling of surface waters. In regions of convergence water piles up and downwelling or, at least, no upwelling occurs. Colder subsurface water is prevented from rising and mixing with the warmer surface water. In regions of divergence, upwelling occurs along with associated mixing of surface water and the colder water upwelled from greater depths.

In Figures 3a-e anticyclonic atmospheric circulation in the region of the anomaly is evident in every month except possibly July. As convergence is associated with this circulation pattern, upwelling was probably weak or negligible during most of the period of the study, thus allowing other forces to heat the surface without much heat lost due to mixing with cooler subsurface waters. Heating of the surface water would produce a stronger thermocline, which in turn would require more intense mixing processes to break down. Convergence probably occurred in September and October and may well have accounted in part for the persistence of the positive temperature anomaly then even though Q_n became negative and winds increased.

6. Interactions of Factors Affecting the Anomaly

In Section 5 the effects of several parameters on the development and maintenance of the SST anomaly were discussed. Obviously all these effects were occurring simultaneously. It may have appeared that one or two of the parameters could have caused the anomaly to develop; however, in this section, it will be shown that if additional parameters had not been conducive to warming, the anomaly would not have come into existence. For example, Q_n may have been large along with strong advection from the south, but if the MLD had been deeper than usual, the winds stronger, or the surface water had been diverging horizontally, the anomalously warm SST's possibly would not have occurred. In this section the combined effects of the parameters will be presented in order to demonstrate how they must have reacted to produce warming conditions.

In Table 1 the monthly sequence of the parameters near the anomaly center is shown. In May the warm advection and high values of Q_n appeared to be an initial impetus to start the warming trend. This trend continued and was augmented in June. Q_n increased, wind speed decreased, MLD was shallower than usual, advection was warmer than normal and horizontal convergence was present. During July, despite decreasing Q_n and cooler advection, the anomaly increased. Apparently the decreasing winds, shallow MLD, and weak convergence, in addition to lags of about a month in response of the surface water to effects of advection and Q_n, cause the anomaly to increase in magnitude.

In August, Q_n continued to decrease to about half the seasonal maximum and advection was near normal, yet the anomaly reached its maximum magnitude. Here the importance of shallow MLD and convergence seems to be evident. Reduced mixing with cooler water from subsurface layers and a thinner layer of water to be heated allowed warming of the surface layer.

Parameter		May	Jun	Jul	Aug	Sep	Oct
Anomaly Maximum		(diffuse) +0.5	+1.3	+2.1	2.8	+2.1	+1.5
$Q_n(\frac{g\text{-cal}}{cm^2\text{-day}})$		300-365	370-455	320-345	200-250	40-120	-40 - -120
Wind Direction		SW	SSW	NW	SW-W	WNW-N	VRBL
Wind Speed (Kts)		17-22	15-16	7-12	10-12	8-11	8-18
MLD (m)	normal	---	18-38	21-30	18-30	23-46	29-53
	1967	---	20-28	14-20	14-22	20-24	24-38
Converg.-Diverg.		---	conv	weak conv	conv	weak conv	conv
Advection		warmer	warmer	cooler	normal	normal	normal
Movement of Anomaly		---	---	ESE 0.4kt	E 0.4kt	SSE 0.4kt	S 0.3kt

Table 1. Monthly sequence of parameters in the area of the anomaly. Advection is compared to normal.

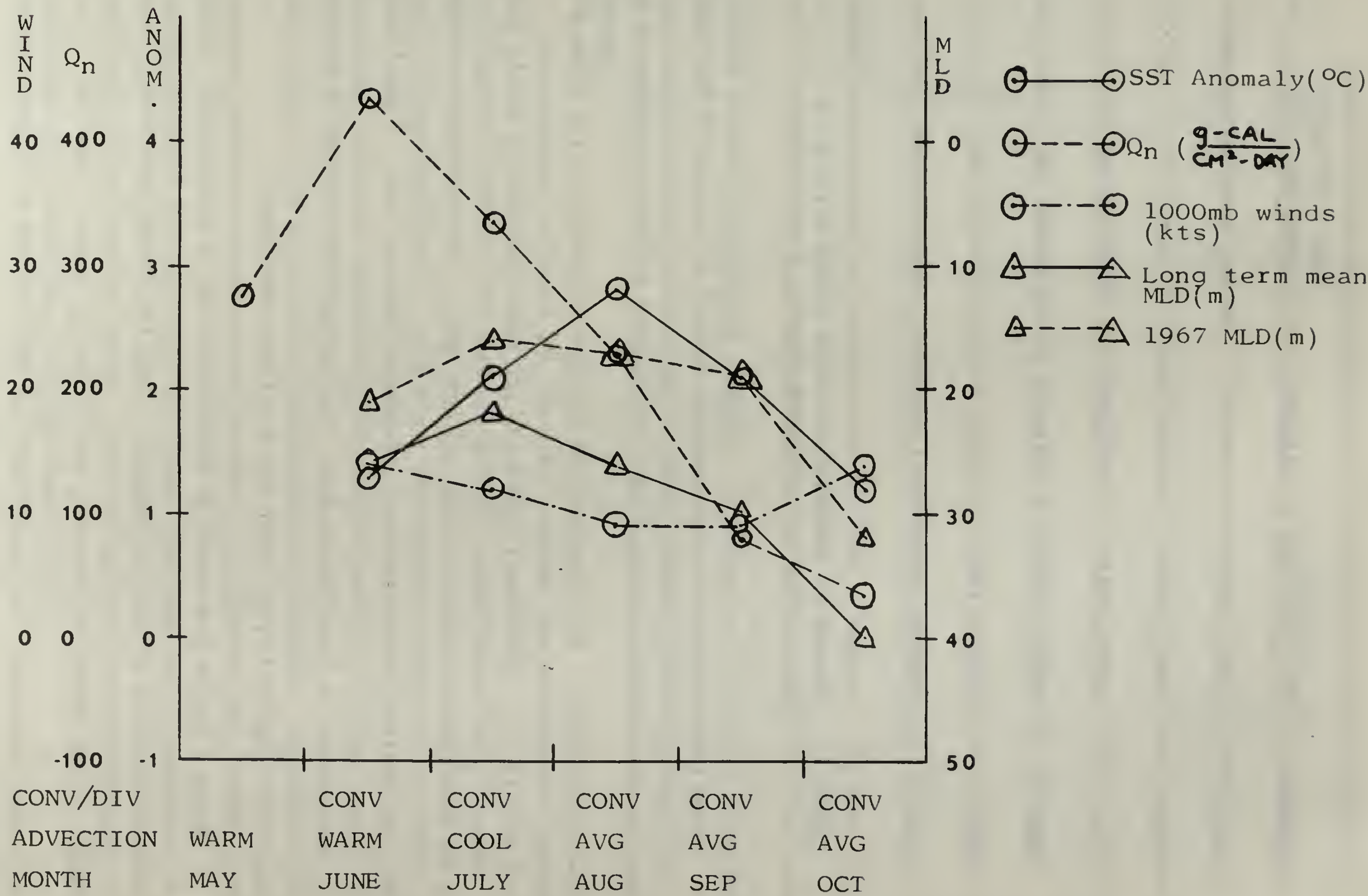

Figure 9. Monthly sequence of parameters at positive anomaly maximum.

Month	Q_n $\left(\frac{\text{g-cal}}{\text{cm}^2\text{-day}}\right)$	MLD (m)	temp. change in mixed layer ($^{\circ}C$)
May	320 to 365	----	0.1 to 0.2 (approx)
June	370 5o 455	20 to 48	.13 to .22
July	320 to 345	14 to 20	.15 to .25
Aug	200 to 250	14 to 22	.10 to .18
Sep	40 to 120	20 to 24	.01 to .06
Oct	-40 to -120	24 to 38	less than 0

Table 2. Change in temperature in the mixed layer as a function of net heat exchange (Q_n) and MLD.

From May to August an appreciable amount of heating of the mixed layer at the anomaly maximum was contributed by heat exchange at the air-sea interface. The temperature changes indicated in the table are due only to Q_n. Additional effects of the other parameters would have to be determined to arrive at the net heat gain. The effect of a shallow MLD on heating can be seen by comparing June and July. Even though Q_n was higher in June than in July, the temperature change in the mixed layer was greater in July when the MLD was shallower.

When a lag of one month in response to Q_n is considered, the greatest heating occurred in July and August. This lag could have been a significant cause of the continued warming well after Q_n began to decline. The lag may also have aided the persistence of the anomaly in September and October.

Further effects of interactions of the parameters can be seen in Figure 10. The data displayed are for a position (40N 140W) through which the anomaly passed. Effects associated with its development and decline can be seen. In May, June and July, Q_n was high, winds were decreasing or relatively low, MLD was shallower than usual, advection was warm, and convergence occurred (June only). As the anomaly declined, conditions changed. Q_n decreased and became negative, MLD was near normal, winds increased, advection was normal, and horizontal convergence-divergence can be seen in August. Q_n was high, winds relatively light, and the MLD was slightly shallower than normal, yet the anomaly <u>decreased</u> slightly. Divergence in the area must have been sufficient to induce slight cooling through upwelling and wind mixing.

In contrast to Figure 10, Figure 11 shows the sequence of parameters at a position (43N 155W) through which a negative anomaly passed. It can be seen that high Q_n and warm advection in May and June were not sufficient to cause appreciable anomalous heating. Strong winds, MLD near normal, and divergence prevented much warming. In August the anomaly became negative even though Q_n (lag) was high, winds were relatively light and MLD was shallower than normal. Divergence in the area and cool advection (recall possible lag discussed previously) must have been sufficient cause for the water to cool.

All the ways in which the parameters interact cannot possibly be discussed here. It is believe that the major interactions have been

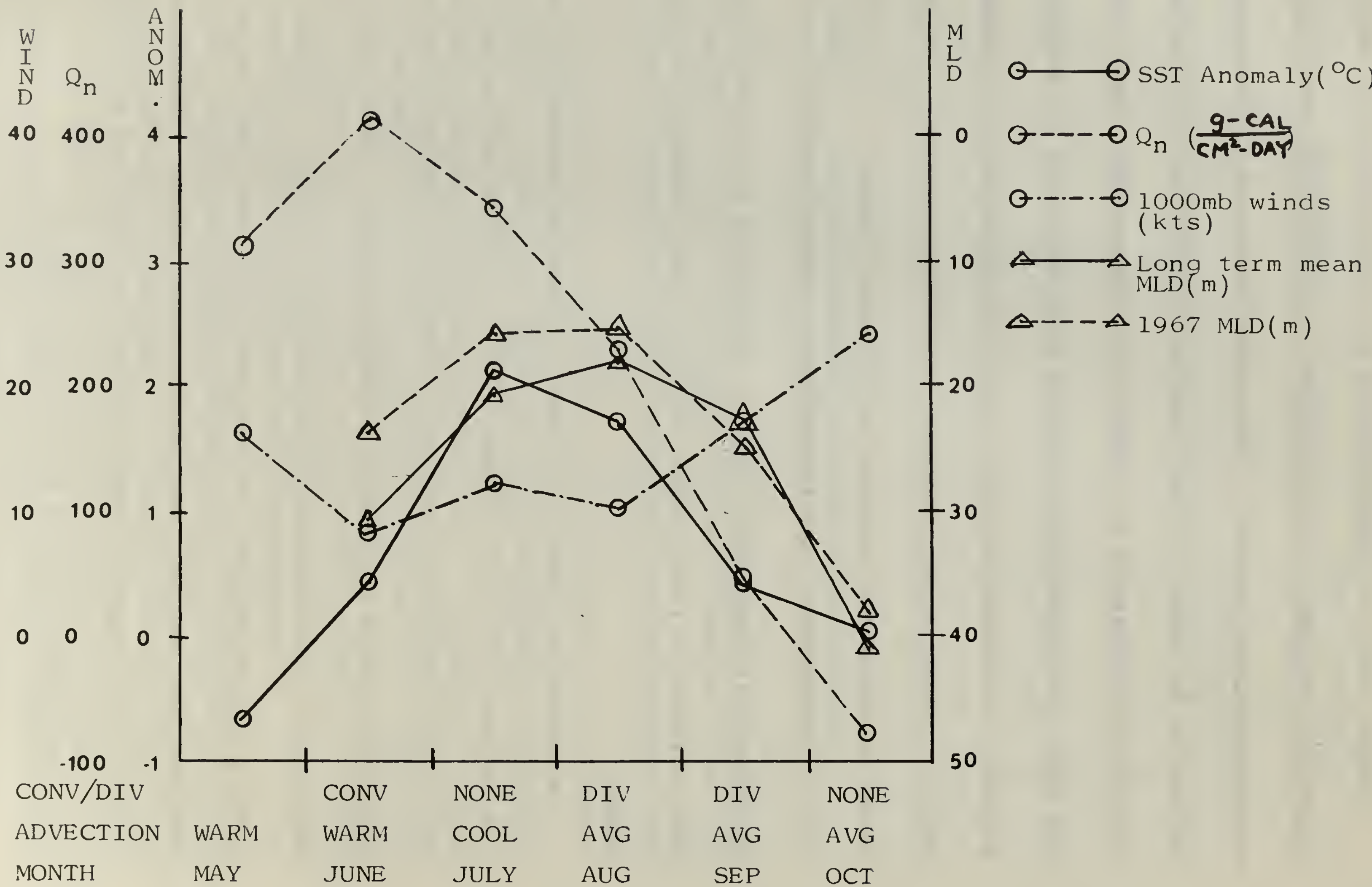

Figure 10. Monthly sequence of parameters at a point(40N 140W) through which the positive anomaly passed.

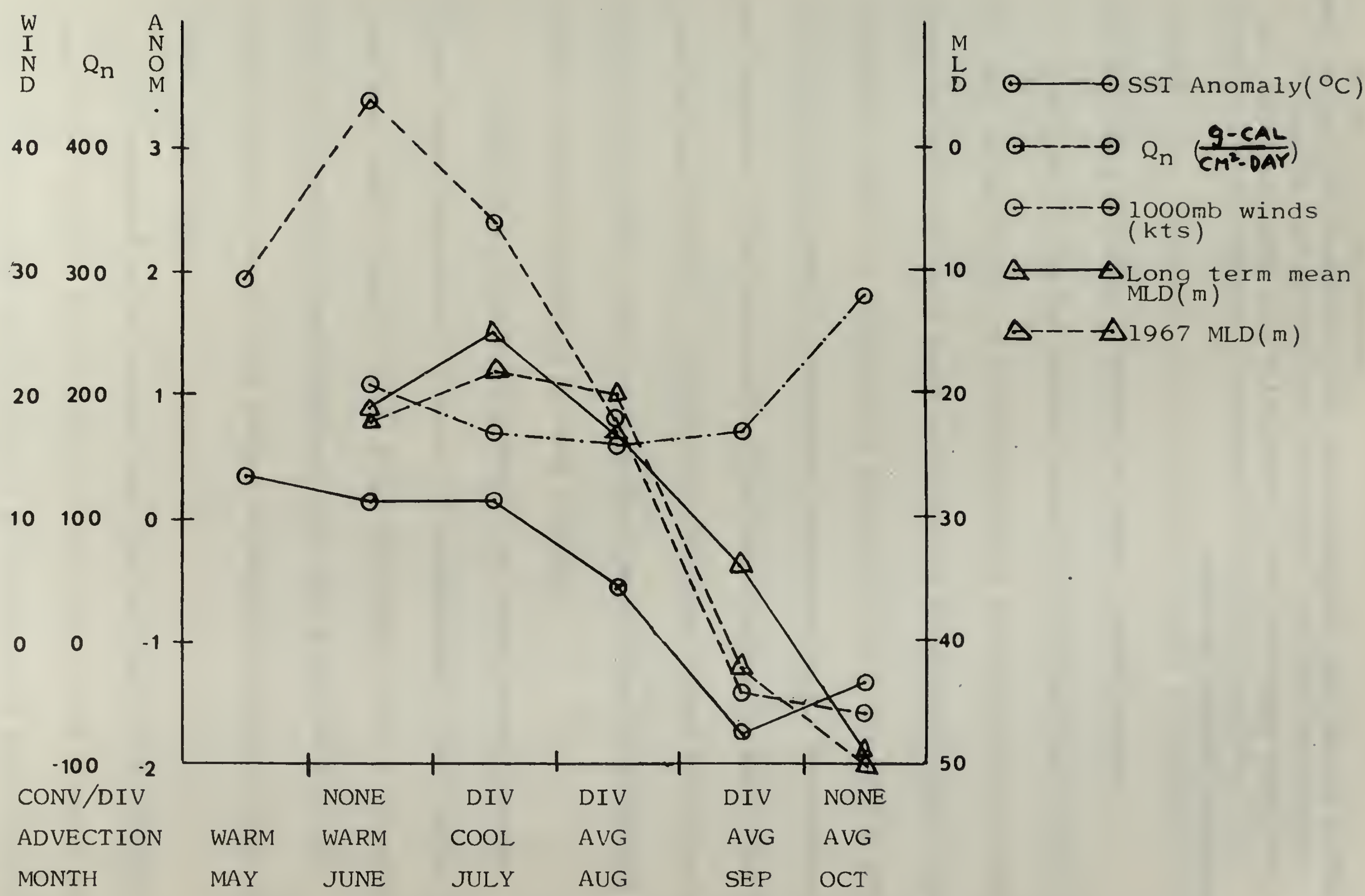

FIGURE 11. Monthly sequence of parameters at a point (43N 155W) through which a negative SST anomaly passed. Note shift in scale of anomaly magnitude.

pointed out and that conditions have been described that must be present in sufficient magnitude and in combination with other parameters for anomalous heating to occur.

7. Movement of the Anomaly

It appears that the anomaly, in general, followed the surface currents through October. Comparing the monthly positions of the anomaly (Fig. 2a-e) with the mean surface currents for summer (Fig. 12) one can see a tendency to follow the general current pattern.

From June to July the anomaly moved eastsoutheastward at about 0.5 knot (using centers of monthly positions for direction and speed). Both direction and speed agree with those of the summer surface currents as shown in Fig. 12. From July to August movement was east at about 0.3 knot and the anomaly diverged or spread out toward the northeast and southeast. The divergence of the North Pacific Current in this region could account for this. Throughout the remainder of the period the main body of the anomaly moved southsoutheastward along the California coast at speeds comparable to local currents.

A tongue of warm water appeared to be carried north along the Alaska coast in the Alaska Current. This advection of warm water must have been fairly strong as winds in the area were between 15 and 29 knots, heat exchange was between 0 and -360 g-cal/cm^{2}day, and MLD's were deepening to the north. Horizontal convergence may have had an effect here.

The movement of the anomaly can also be related to the 1000mb winds (Fig. 13a-d). In this Figure, 5-day means of the anomaly one month apart were used as they give a better picture of the movement of the anomaly. Movement during July is toward the southeast, the same

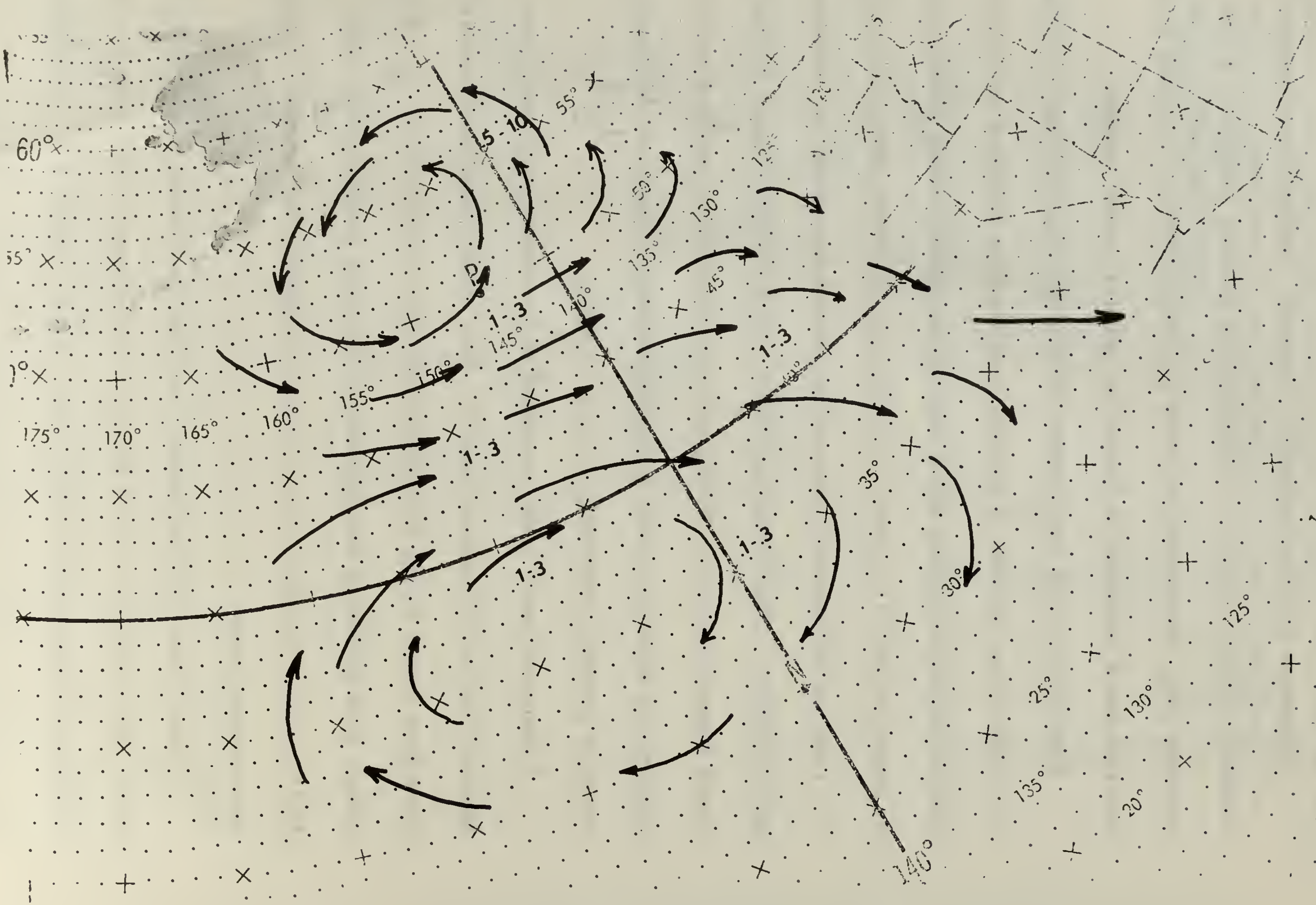

Figure 12. Summer surface currents, NE Pacific. Speeds in knots.

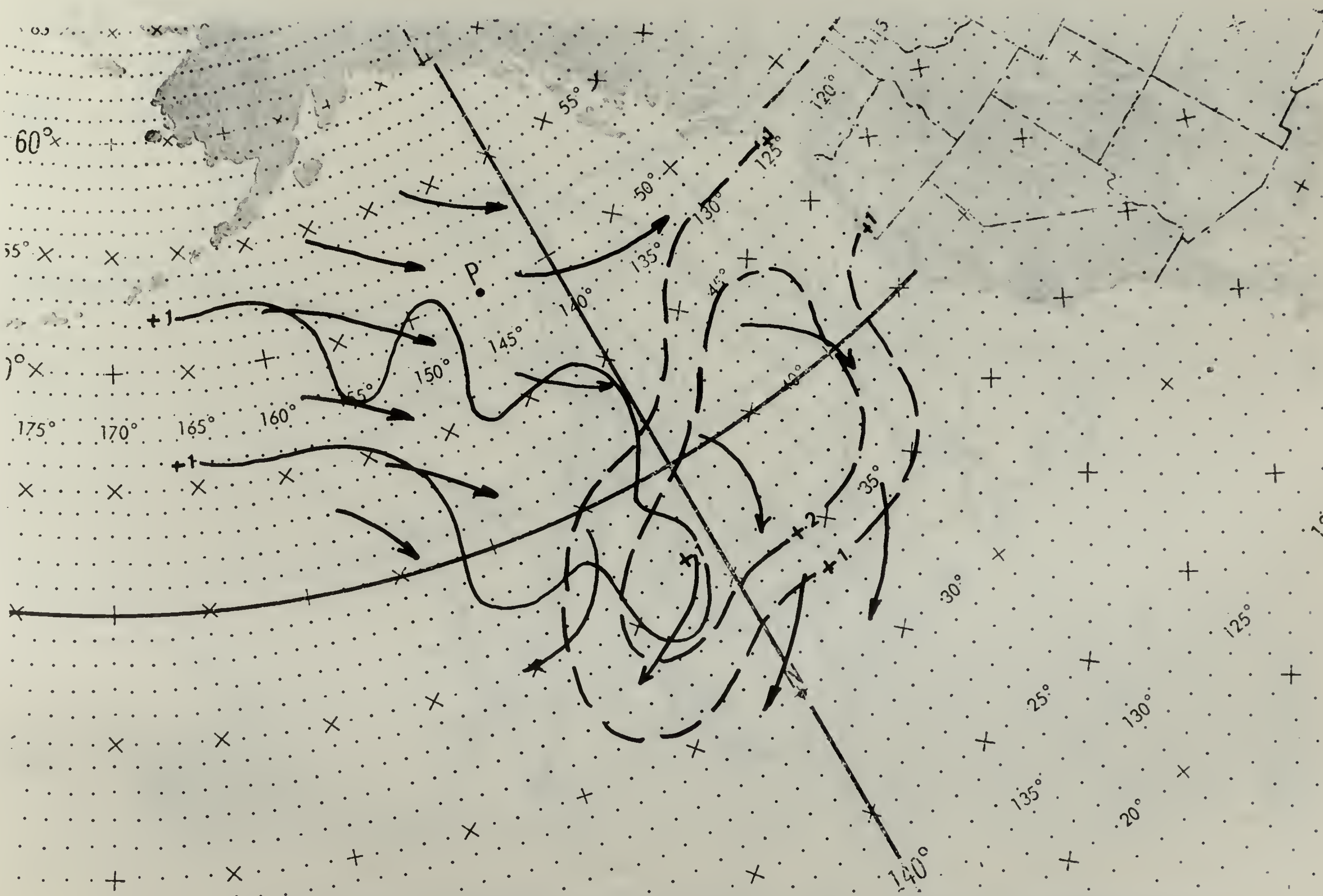

Figure 13a. Movement of positive SST anomaly with respect to 1000mb winds. 30 June 5-day mean SST anomaly solid, 30 July 5-day mean SST anomaly dashed, arrows July 1000mb winds.

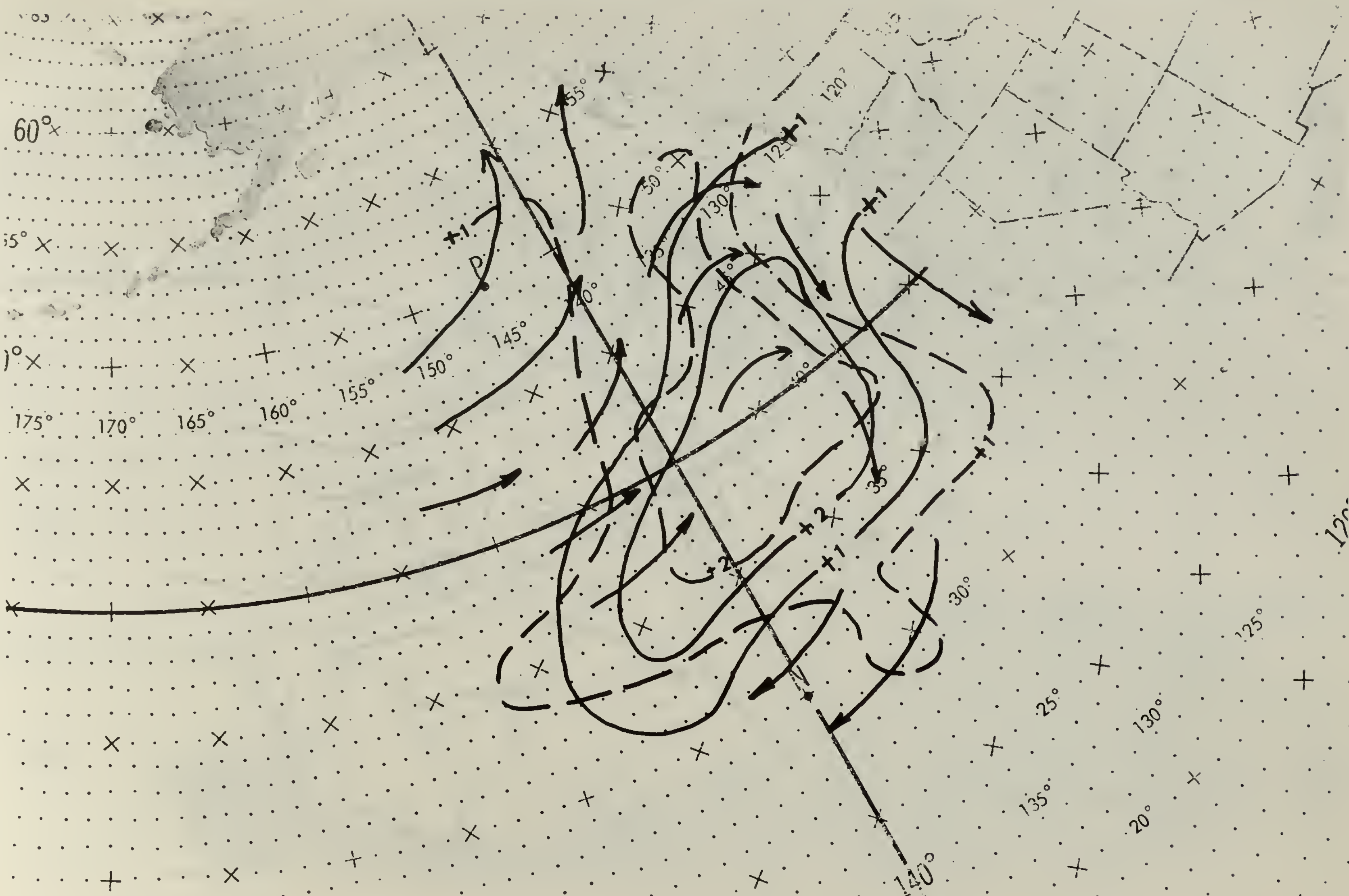

Figure 13b. Movement of positive SST anomaly with respect to 1000mb winds. 30July SST anomaly solid, 30 August 5-day SST anomaly dashed, arrows August 1000mb winds.

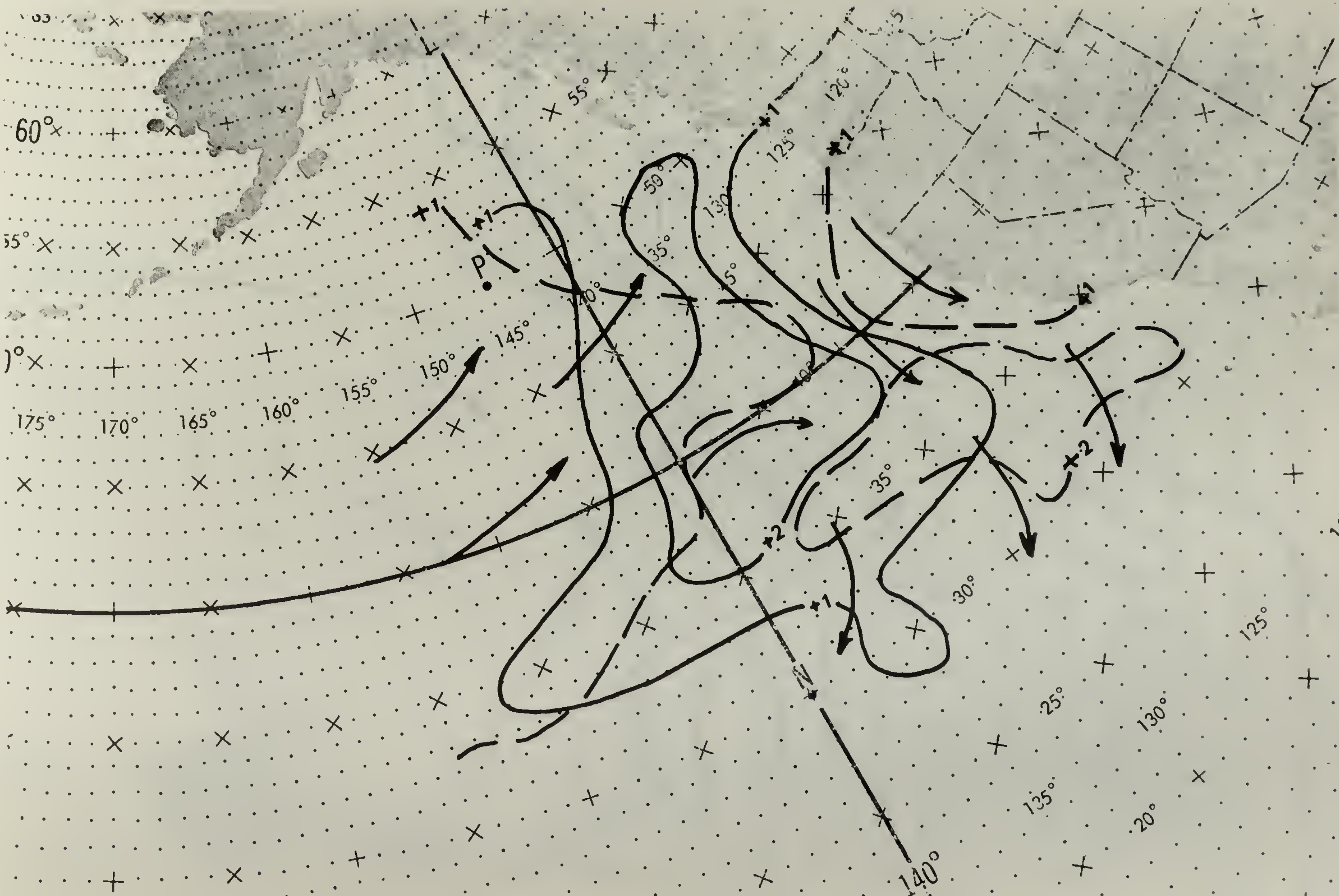

Figure 13c. Movement of positive SST anomaly with respect to 1000mb winds. 30 August 5-day mean SST anomaly solid, 25 September 5-day mean SST anomaly dashed, arrows September 1000mb winds.

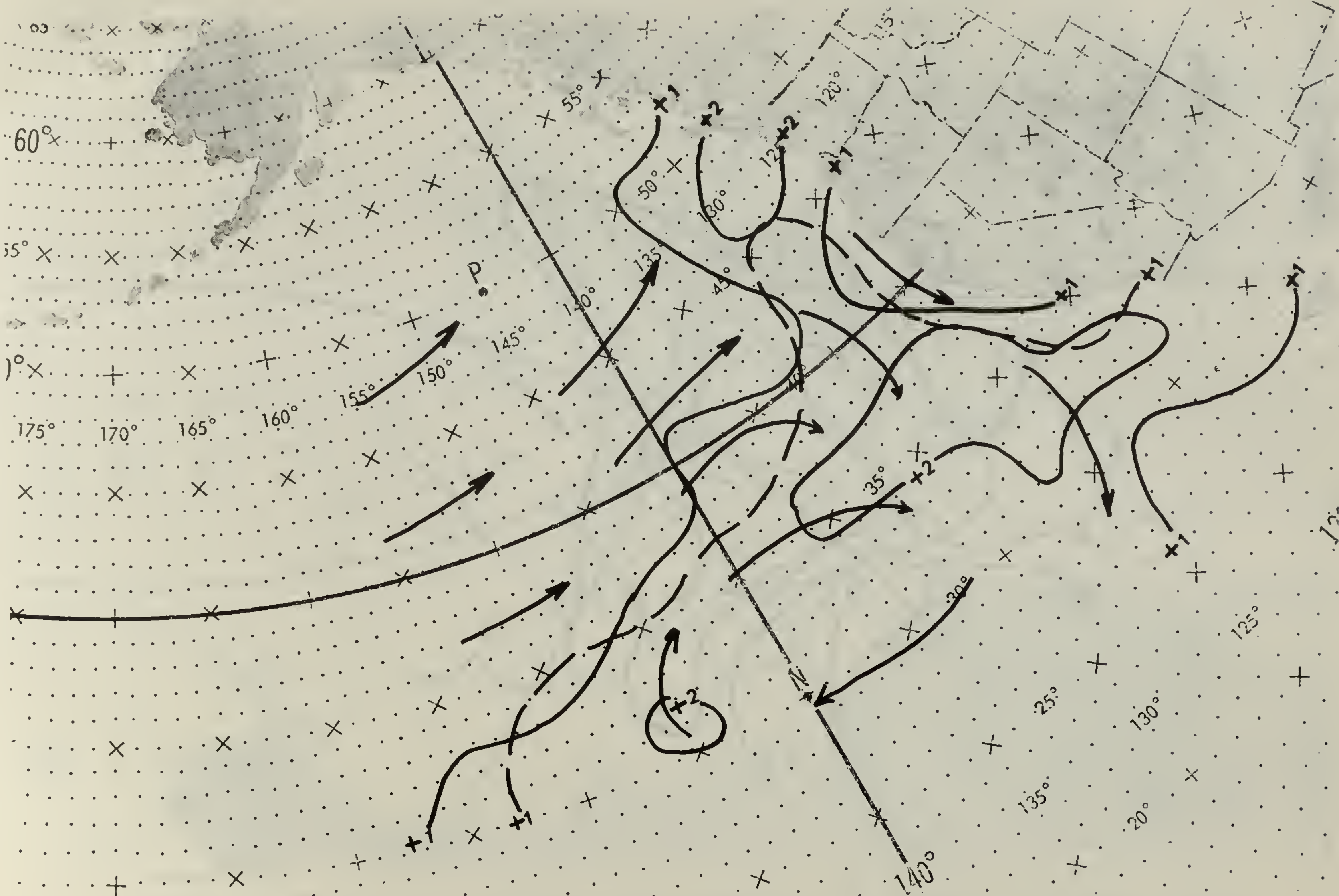

Figure 13d. Movement of positive SST anomaly with respect to 1000mb winds. 25 September 5-day mean SST anomaly solid, 25 October 5-day mean SST anomaly dashed, arrows October 1000mb winds.

direction as the mean 1000mb winds for the month. During August the center of the anomaly moved toward the northeast although the overall boundary position remained stationary. Movement of the isopleths of temperature anomaly in the west and southeast portions followed the mean winds in those areas. Westerly winds in the western portion produced movement toward the east and northerly winds in the southeast produced movement toward the south. During September the anomaly moved to the southeast while winds were northerly. Although this movement with respect to the wind is not as clear-cut as previously, two explanations are possible: (1) surface currents were directed more to the southeast or (2) the western portion of the anomaly was dissipated giving the appearance of movement to the southeast. In October there was little movement of the anomaly. Anticyclonic atmospheric circulation covering most of the area could account for the lack of movement.

8. Uses of SST Anomaly Data

The idea of feedback processes to the atmosphere caused by abnormally warm (or cold) ocean waters will be an important consideration in future long-range weather forecasting. As this field has yet to be investigated in detail and a study was not attempted in this report, only general observations with possible explanations will be made.

Namias (1959), in an attempt to find a long-range forecasting tool, investigated relations between SST anomalies and cyclone movement. He found evidence that cyclogenesis and intensification was due in part to interactions between abnormally warm surface water and the atmosphere. The warm water provided an initial impetus for cyclogenesis and intensification and then the water was kept warm by factors associated with increased cyclonic activity. Namias postulated that a storm would gain energy from the heat and moisture supplied by the water. It would then cause an increase in the vertical ascent of air and thereby release latent heat of vaporization which would tend to deepen the storm further.

During the period of this study no unusual cyclone activity was noted. In fact, very few storms passed through the regions of the positive anomaly and those that did were very weak, seldom having a central pressure below 1012mb.

Study of monthly mean 700mb heights and height anomalies [Monthly Weather Review, (1967)] for the June-October period indicate a general correlation between the SST anomaly position and anomalous 700mb

heights. After the anomaly became well established (June) there was consistently a positive height anomaly at 700mb over the eastern portion of the warm SST anomaly and a negative height anomaly at 700mb over the western portion of the anomaly and the cold SST anomaly which appeared in the west in July. As the SST anomalies moved in general toward the east and southeast, there was a warming of surface water in the east and cooling in the west. The heated water in turn presumably heated the overlying air causing expansion and, as a result, higher than usual 700mb heights. The cold surface water to the west would have the opposite effect.

The effect, if any, of these anomalous heights on subsequent atmospheric circulation and weather patterns may be important, and further study of feedback relations between SST anomalies and the atmosphere may be of use in future long-range forecasting. That a relationship is indicated in this study and by Namias (1963) shows that more study is needed in this area.

The effect of changes of water temperature upon sound transmission is well known. Ranges to sound convergence zones, active and passive sonar capabilities and use of underwater sound devices depends to a great extent on temperature conditions in the surface layer. Sonar range formulas use as main inputs SST, MLD, and average gradient below the MLD. Obviously anomalous SST temperatures will affect results obtained from using these formulas [Hubert, (1966)] .

Knowledge of anomalous water temperatures and how to use them to advantage or compensate for them could be extremely important to both surface vessels and submarines. The effect of an anomalous region of surface temperatures on the strength of the thermocline, for example, could be used by submarines for avoiding detection and by surface vessels for obtaining the best results from sonar equipment.

An unseasonable warming or cooling of surface waters has a considerable effect on sea life and fisheries. According to Coker (1949) a change in temperature of only a few degrees will cause a significant change in the viscosity of the water. Viscosity has a great effect on ease of movement through the water and upon the ability of marine organisms to maintain certain levels in the water.

Also, most organisms have a limited range of temperatures in which they can exist. Tuna, for example, prefer temperatures within a range of only two or three degrees. Knowledge of anomalous areas and how they will move and whether they will form or disappear will enable commercial fishing fleets to avoid needless searching in areas which have been vacated due to changes in water temperature. Anomalous water temperatures undoubtedly affect spawning times and places and larvae survival.

In Uda's study (1962) of atmospheric and oceanographic phenomena (including SST) and fishery production, he found definte relationships between SST anomalies and atmospheric and oceanic parameters. Conditions of the sea and atmosphere affect reproduction potential and population

strength of fish. Distribution and concentration of fish is also affected by water temperature. Prediction of environmental conditions are becoming vital to the fishing industry as man becomes more dependent upon the sea for food and other resources.

9. Conclusions and Recommendations

This study dealt with the occurrence of a positive SST anomaly in the northeastern Pacific Ocean from May to October 1967, and the environmental parameters that caused its development and dissipation. It examined several apparent relationships between atmospheric and oceanic parameters and anomalous sea surface temperatures. The parameters studied, although all affecting the development of the anomaly to varying extents, are not strong enough to have independently caused the sea surface temperature anomaly observed. Several parameters must have combined to cause sufficient warming of the surface layers for a significant SST anomaly to form. Convergence-divergence and relative mixed layer depth appeared to be very important in the formation of this SST anomaly. The necessary (but not sufficient) conditions for anomalous heating were shallower than normal MLD and horizontal convergence of surface waters. Under these conditions heating by heat exchange at the air-sea interface and advection was most effective.

Two time lags in response of SST to the parameters were noted. Both Q_n and advection appear to have lags of the order of one month in their effect on SST.

Movement of the warm SST anomaly indicated it followed the general direction of the surface currents in the area.

The relations found in this study pertained only to a short period of time and to a relatively restricted ocean area, but it appears that they should hold for general oceanic conditions.

Further study of these relations using smaller scales in both time and space than used in this study, as was briefly attempted herein, would lead to a better understanding of the large-scale interactions. Of special importance would be further study of lag times between atmospheric forces and ocean responses on a scale usable in a forecasting scheme. Investigation of quantitative contributions of each parameter to the development of warm or cold SST anomalies would be valuable in forecasting changes in the sea surface temperature.

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APPENDIX

Comparison of Equations for Net Heat Exchange at the Air-sea Interface Used by Fleet Numerical Weather Facility and the Bureau of Commercial Fisheries, La Jolla

While investigating the effect of net heat exchange, Q_n, at the air-sea interface on the development of anomalous sea surface temperatures, the author found a significant difference in the values of Q_n computed by the Fleet Numerical Weather Facility (FNWF) and the Bureau of Commercial Fisheries (BCF) La Jolla, California. The equations for the various components of Q_n are identical for only two components and differ by varying degrees for the others. The equations used by FNWF and BCF are shown on pages 91 and 92.

Several sets of hypothetical synoptic conditions were selected to show how Q_n and its components can vary. To compute Q_n the sum $Q_r + Q_b + Q_e + Q_h$ is subtracted from Q_s. As the difference in the calculated values of Q_n is due mainly to the greatly differing values of insolation, Q_s, the effect of varying cloud cover is emphasized. Q values for four sets of conditions, A1, A2, A3, and B, are shown in Tables 3 and 4. Conditions A1, A2, and A3 are the same except for varying the cloud cover. Condition B is entirely different.

With clear skies (A1), Q_n is about the same for both methods. The difference in Q_s ($119 \frac{\text{g-cal}}{\text{cm}^2\text{-day}}$) was compensated for by the variations in computed values for the other components. As cloud cover increases

(A2 and A3) the difference in Q_s becomes greater and cannot be compensated for by the differences in the other components. Thus, the difference in Q_n is larger as cloud cover increases (see Table 3).

Condition A   1 June, 40N 140W

t_d	(hours of sunlight)	= 15	V	(wind speed)	= 5m/sec
T_w	(water temperature)	= 18°C	U	(rel. humidity)	= 73%
T_a	(air temperature)	= 20°C	e_a	(air vapor press.)	= 14mb
T_d	(dew-point temp)	= 15°C	e_w	(water vapor press.)	= 19mb

	A1		A2		A3	
clouds	0/10		4/10		8/10	
	FNWF	BCF	FNWF	BCF	FNWF	BCF
Q_s	908	789	864	620	628	359
Q_r	57	47	56	37	55	22
Q_b	192	165	133	125	74	72
Q_e	196	117	196	117	196	117
Q_h	-30	-30	-30	-30	-30	-30
Q_n	493	490	509	371	333	178

Table 3. Comparison of values of components of Q_n for given sets of conditions (A).

Under conditions B all parameters except data and location are changed. The large difference in Q_n was again due to the large difference in the values of Q_s. After the respective subtractions were

performed, the difference in Q_n, though reduced somewhat, was still significant (see Table 4). In every case the sum $Q_r + Q_b + Q_e + Q_h$ as computed by FNWF was larger than that computed by BCF.

<u>Condition B</u> 1 June, 40N 140W

t_d = 15hr.	V = 10m/sec	cloud cover = 8/10
T_w = 16°C	U = 81%	
T_a = 17°C	e_a = 14mb	
T_d = 14°C	e_w = 17mb	

	FNWF	BCF
Q_s	628	359
Q_r	55	22
Q_b	72	79
Q_e	182	141
Q_h	-32	-32
Q_n	351	149

Table 4. Comparison of values of components of Q_n for a given set of conditions (B).

It is not within the scope of this thesis to conduct an investigation of net heat exchange. Yet, the variability of computed values of Q_n shows that several schools of thought still exist. A brief term-by-term comparison of the two equations follows on page 93.

Term	FNWF	BCF
Q_n	$Q_s - Q_r - Q_b - Q_e - Q_h$ (after Laevastu, (1960)	$Q_s - Q_r - Q_b - Q_e - Q_h$
Q_s	$Q_{Os} = 0.014 A_N t_d$ Q_s = minimum of $Q_{Os}(1 - .0075(Cl)^3)$ $Q_{Os}(1 - .0060(Cm)^3)$ $Q_{Os}(1 - .0035(Ch)^3)$ Q_{Os} = 24hr insolation for clear sky A_N = noon altitude of the sun t_d = length of daylight (sec) Cl = low clouds (tenths) Cm = mid clouds (tenths) Ch = high clouds (tenths)	$B(1 - aC - bC^2)$ (after Berliand, 1960) B = insolation for clear sky a = function of latitude b = 0.38 C = cloud cover (tenths)
Q_r	$0.15Q_s - (0.01Q_s)^2$	$Q_s \times r$ (after Budyko, 1956) r = % of Q_s reflected (function of latitude)

Term	FNWF	BCF
Q_b	$Q_{Ob} = 297 - 1.86T_w - 0.95U$	$s\sigma T_w^4(.39-.05e_a)(1-kC) + 4s\sigma T_w^3(T_w-T_a)$
	Q_b = minimum of:	(after Berliand and Berliand, 1952)
	$Q_{Ob}(1-.085Cl)$	s = .97 (ratio of radiation of sea surface to that of black body)
	$Q_{Ob}(1-.065Cm)$	$\sigma = 1.175\text{x}10^{-7}$ (Stefan-Boltzman const.)
	$Q_{Ob}(1-.030Ch)$	e_a = vapor pressure of air
	Q_{Ob} = back radiation with clear sky	k = constant (function of latitude)
	U = relative humidity	T_w = water temperature
		T_a = air temperature
Q_e	$(.26+.077V)(e_w-e_a)(.06T_w-59.6)$,	$4.70(e_w-e_a)V$ (after Jacobs, 1951)
	$(e_w-e_a) > 0$	e_w = vapor pressure at SST
	$.077V(e_w-e_a)(.06T_w+59.6)$, $(e_w-e_a) < 0$	V = wind speed (m/sec)
Q_h	$39(.26+.077V)(T_w-T_a)$, $T_w-T_a > 0$	$3(T_w-T_a)V$ (after Bowen, 1926)
	$3V(T_w-T_a)$, $T_w-T_a < 0$	

Comparison of terms

The following discussion pertains only to the period and region of this study. Latitudinal effects below 30N have not been considered here but would have definite effects on comparative values of Q_s and Q_r.

Q_s, incoming solar radiation

Q_s accounts for the net difference between the two computed values of Q_n for a given set of conditions. At a given location with clear skies the FNWF value of Q_s is higher than that of BCF. In addition, BCF reduces Q_s by a greater percentage than FNWF for a given cloud cover and location as shown below.

Clouds	Q_s	FNWF Reduction of Q_s	Q_s	BCF Reduction of Q_s
0	908	-----	789	-----
4/10	964	5%	620	21%
8/10	638	31%	359	54%
10/10	364	60%	189	76%

As the value of Q_s depends greatly on cloud cover, one should look at how FNWF and BCF arrive at the amount of clouds used in the computations. FNWF uses entirely numerical methods. A special computer program using empirical rules relating atmospheric parameters at 300mb, 500mb, and the surface to cloud cover is used as input to their heat exchange program [Hughes (1966)] . BCF uses only synoptic reports with rules regulating the use of these data.

Q_r, radiation reflected at the sea surface

The formula used by BCF calls for less reflection per unit insolation than that of FNWF. The values of Q_r differ by greater amounts as the cloud cover increases because BCF computations for Q_s are smaller, as shown in tables 3 and 4. As Q_r is only a small part of Q_s, the difference in the computed values do not greatly influence Q_n. Also, since Q_r is subtracted from Q_s, the relative difference between the two values of Q_s is decreased by the Q_r difference.

Q_b, effective back radiation

Despite the difference in appearance of the two equations, the computed values do not differ greatly except when cloud cover is low (3/10 or less). Even then under a given set of conditions (A1) the difference was less than 30 $\frac{\text{g-cal}}{\text{cm}^2\text{-day}}$.

Q_e, heat exchange due to evaporation and condensation

Equations used by FNWF and BCF are functions of wind speed and vapor pressure. The FNWF equation is also a function of water temperature, but only to a small extent. FNWF uses two equations, one for evaporation, the other for condensation, while BCF uses the same equation for both situations. Expanding FNWF's equation for condensation heat exchange and eliminating the small T_w term shows it to be the same as the BCF equation. The fact that BCF doesn't

consider the change in direction of transfer of latent heat accounts for the different values of Q_e. As $e_w - e_a$ becomes larger, the difference is computed values of Q_e becomes smaller.

Q_h, exchange of sensible heat

As with Q_e, BCF uses only one equation for the transfer of sensible heat from air to sea and vice versa while FNWF uses a different equation for each situation. For heat transfer from air to sea the equations are identical, but for heat transfer from sea to air the computed values of Q_h differ considerably as shown below.

V(m/sec)	$T_w - T_a$ (°C)	Q_h ($\frac{\text{g-cal}}{\text{cm}^2\text{-day}}$) FNWF	BCF
5	+4	100	60
5	+2	50	30
5	-2	-30	-30
5	-4	-60	-60

Summary

The great difference in the values of Q_n obtained and used by FNWF and BCF in their operations show the variation of opinion and method in determination of net heat exchange across the air-sea interface. Many empirical and theoretical equations for the components of heat exchange have been developed; but until more comprehensive and accurate synoptic marine observations are availabe, it will continue

to be impossible to determine which formulas are most correct. Until such accuracies are attained these formulas can be used only to indicate large scale features of net heat exchange on a synoptic basis. The value of heat exchange calculations, though of uncertain accuracy, lies in showing monthly or annual variations of the parameter. "Until such time as these computations can be improved to represent the absolute values, they should be considered only as relative indices of the total energy flux at the air-sea interface" [Johnson, (1965)].

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13. ABSTRACT

Factors affecting the heat content of the ocean's surface layer are briefly discussed. Some recent studies of sea surface temperature (SST) anomalies are reviewed. The SST anomaly in the NE Pacific, June-October 1967, is described. The influence of individual parameters (1000mb wind, advection, mixed layer depth, net heat exchange, convergence-divergence) on the development and dissipation of the SST anomaly under investigation is evaluated. The simultaneous interactions of the parameters during the period of the study are discussed. Movement of the SST anomaly is described. Warmer than usual advection of surface water and high values of net heat exchange were necessary but not sufficient conditions for development of the SST anomaly. The critical importance of horizontal convergence in the surface layer and relatively shallow mixed layer depth is determined.

14. KEY WORDS	LINK A		LINK B		LINK C	
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